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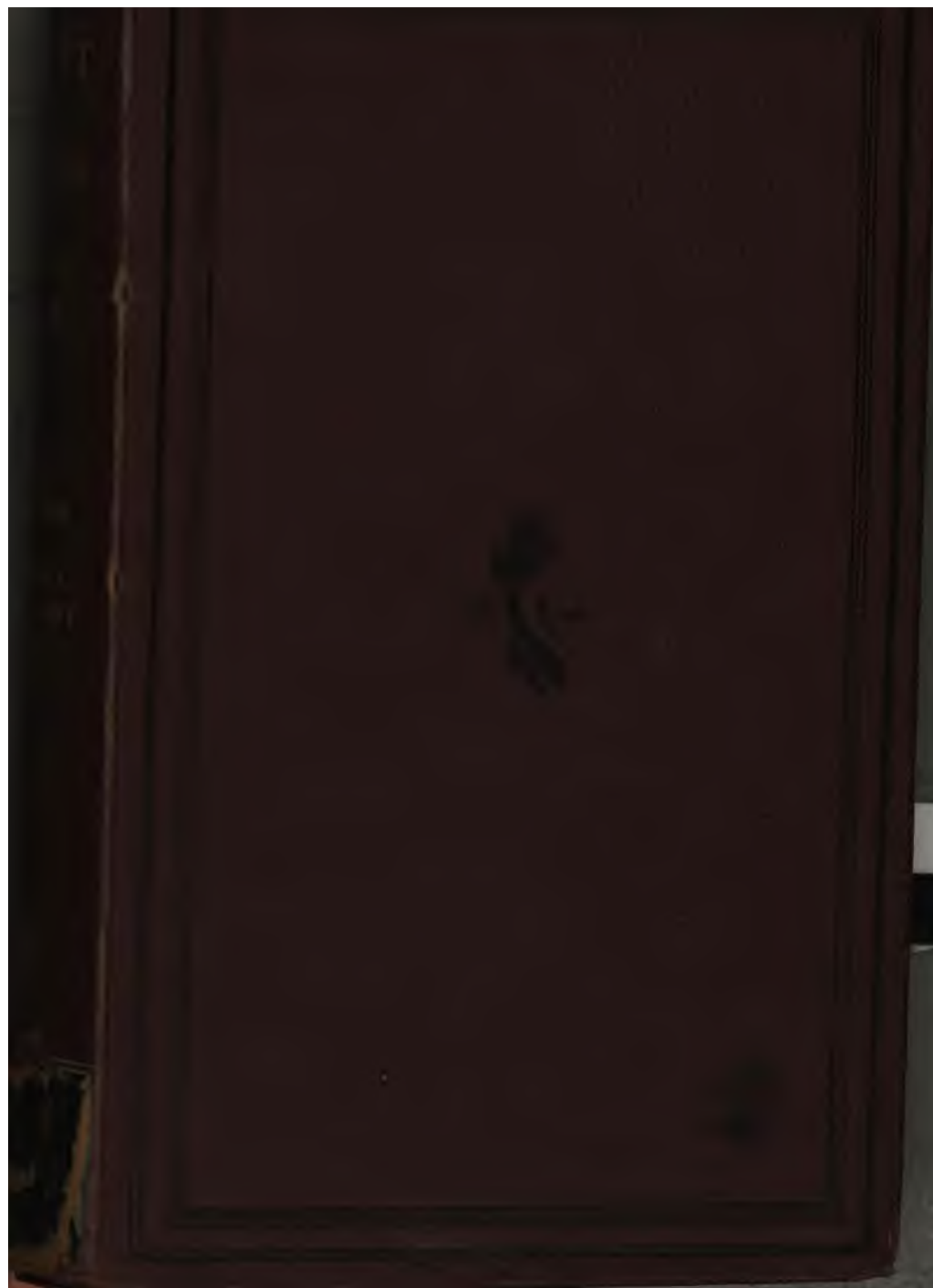
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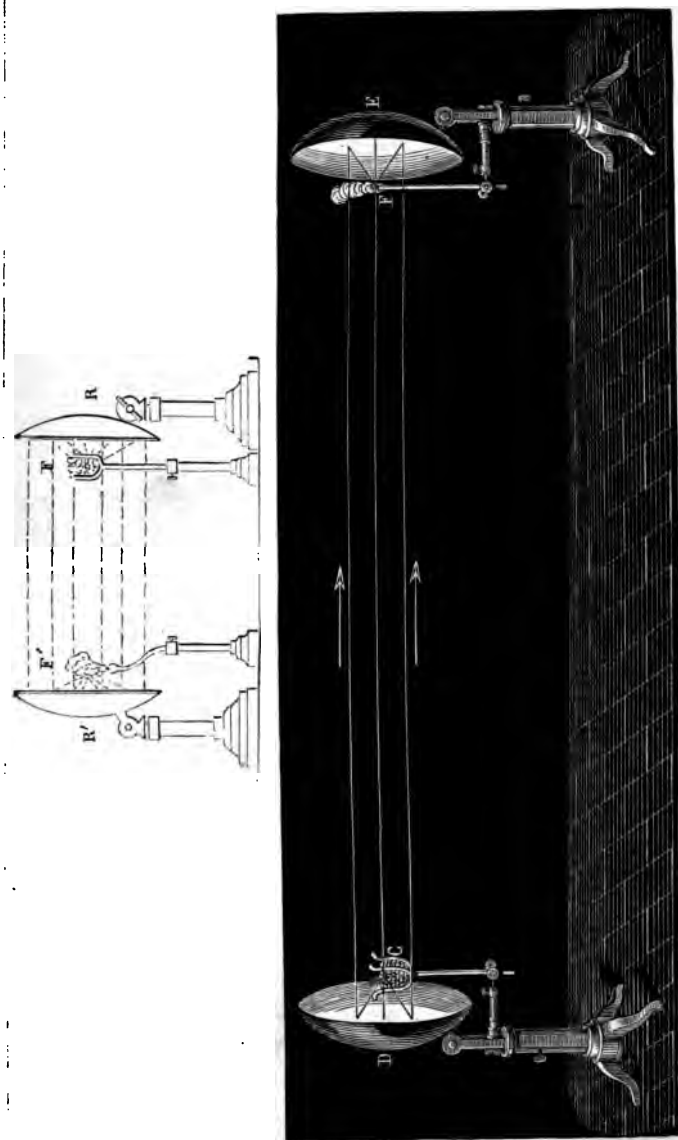
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RADIATION.

HANDBOOK OF NATURAL PHILOSOPHY.

BY
DIONYSIUS LARDNER, D.C.L.
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IN UNIVERSITY COLLEGE, LONDON.

HEAT.

NEW EDITION.

EDITED AND ALMOST ENTIRELY REWRITTEN BY
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THE Second Volume of Lardner's original *Handbook of Natural Philosophy* contained two parts : one on *Hydrostatics*, *Pneumatics*, and *Hydrodynamics* ; the other on *Heat*. The considerable additions which have been made in recent times to our knowledge of the phenomena of Heat and to their theoretical interpretation, rendered it necessary to devote a separate volume to the subject, and to give it more adequate treatment. Consequently the present treatise on HEAT contains about three hundred and twenty pages of new matter, embodying all the more important researches in this branch of Physics up to the present day ; while even the small portion which has been transferred from the original work had to be remodelled and brought in accord with modern terms and views. The editor has endeavoured to present the facts in the most simple language, adapted to the beginner in this subject and to the general reader. A special chapter has been devoted to appli-

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cations and problems, in which the present requirements of students preparing for public examinations have been kept in view. It is hoped that such readers will find much help in their studies from the matter thus placed before them in an easily accessible and collected form.

January, 1877.

P R E F A C E .

THIS work is intended for all who desire to attain an accurate knowledge of Physical Science, without the profound methods of Mathematical Investigation. Hence the explanations are studiously popular, and everywhere accompanied by diversified elucidations and examples, derived from common objects, wherein the principles are applied to the purposes of practical life.

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H E A T.

BOOK THE FIRST.

GENERAL EFFECTS OF HEAT UPON BODIES.

EXPANSION, AND CHANGE OF STATE OF AGGREGATION.

CHAPTER I.

PRELIMINARY PRINCIPLES.

1. There are certain changes in the condition or state of bodies which are referred to a physical agency called *Heat*. One of the most familiar effects of this agency is the sense of more or less warmth which a body produces upon our organs. We call a body *cold*, or *warm*, or *hot*, according to the difference in certain sensations produced by the body ; and if these sensations, which inform us of the state of bodies with reference to heat, were under all circumstances trustworthy, and at all times comparable, we should at once possess the means of subjecting the phenomena of heat to close investigations without the necessity of employing special instruments designed for measuring the changes in the state of *sensible* heat of bodies, or more briefly, the changes in the *temperature* of bodies.

2. But the senses, though appealed to by the whole world as the most unerring witnesses of the physical qualities of bodies, are found, when submitted to the severe scrutiny of the understanding, not only not the best sources of exact information as to the qualities or degrees of the physical principles by which they are severally affected, but the most fallible guides that can be selected, often informing us of a quality which is absent, and of the absence of one which is present.

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Nor should this be any matter of surprise. Our organs of sense are not designed to be philosophical instruments. The eye, the ear, and the touch, though admirably adapted to serve our purposes, are not severally a telescope, a monochord, and a thermometer. An eye which would enable us to see the inhabitants of a planet would probably ill requite its owner for that ruder power which guides him through the town he inhabits, and enables him to recognise the friends who surround him. The comparison of the instruments which are adapted for the uses of commerce and domestic economy with those destined for scientific purposes supplies an appropriate illustration of these views. The delicate balance used by the chemist in determining the analysis of the bodies upon which he is engaged would, by reason of its very perfection and sensibility, be utterly useless in the hands of the merchant or the housewife. Each class of instruments has, however, its peculiar use, and is adapted to give indications with that degree of accuracy which is necessary, and required for the purposes to which it is applied.

3. The touch is the sense by which we acquire a perception of heat. It is evident, nevertheless, that it cannot inform us of the quantity of heat which a body contains, much less of the relative quantities contained in any two bodies. For not all heat is *sensible*, that is, heat attended by a sense of increased or diminished warmth. It occurs in many cases that a body may receive a very large accession of heat without any increased sense of warmth being produced by it, and may, on the other hand, lose a considerable quantity of heat without exciting any diminished sense of warmth. The heat which a body thus receives or loses without affecting the senses has been called *latent heat*.

In no case is the sense of touch affected by latent heat, and it can thus give no indication of the fact that a solid lump of ice and a quantity of ice cold water, although both may be of the same *temperature*, contain very different *quantities* of heat.

4. But it may be said that even the thermometer does not in this case indicate the presence of the excess of heat in the liquid. The sense of feeling will, however, be found almost as fallacious as regards the temperature of bodies; for it is easy to show that the sense of warmth depends as much upon the condition of the part of the body which touches or is surrounded by the warm or cold medium, as on the temperature of that medium itself.

If the two hands be plunged, one in water which is very hot *and* the other in water which is very cold, and being held there

for a certain time both are transferred to water of an intermediate temperature, this water will appear warm to the hand which had been plunged in the cold water, and cold to the hand which had been plunged in the hot water.

If on a hot day in summer we descend into a deep cave, it will feel cold ; if we descend into the same deep cave on a frosty day in winter, it will feel warm ; yet a thermometer in this case will prove that in the winter and in the summer it has very nearly the same temperature.

These anomalies arise from the fact that all our sensations are relative. When the body has been exposed to a high temperature, a medium which has a lower temperature will feel cold, and the same medium will feel cold if the body has been exposed to a lower temperature.

5. If in a room raised to a high temperature, as in a vapour or hot-air bath, we touch with the hand different objects, they will appear to have very different temperatures ; a woollen carpet will feel cold, marble slabs warm, and metal objects very hot. If, on the other hand, we are in a room at a very low temperature, all these properties will be reversed ; the carpet will feel warm, the marble slabs cold, and the metallic objects colder still.

These effects depend on the different behaviour of bodies with reference to heat. Thus a woollen carpet belongs to a class of bodies called non-conductors of heat. When surrounding objects are at a more elevated temperature than that of the body, the woollen carpet partaking in this temperature will, when touched, feel cool, because, being a non-conductor of heat, the heat which pervades it does not pass freely to the part of the body which touches it. A marble slab being a better conductor, and a metallic object a still better, the heat will pass from them more freely to the part of the body which touches them, and they accordingly appear hotter.

But if the room be at a temperature much lower than the body, then when we touch the woollen carpet the heat does not pass from our body to the carpet, because it is a non-conductor, and as we do not lose heat, the carpet feels warm ; but when we touch the marble, and still more a metallic object, the heat passes more and more freely from our body to these objects, and being sensible of a loss of heat more or less rapid, we feel cold.

6. It will be evident from facts like those stated in the preceding article, that the truthful pursuit of all inquiries about heat must depend in the first instance on rejecting all information derived from our senses alone. In order to obtain more

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trustworthy means of studying heat, it will become necessary to take a preliminary survey of the general effects of heat, and to examine whether these effects do not in themselves present some guide better adapted to the discovery of truth than our sensations, and it will be advantageous to the student to introduce here at the same time the definitions of some terms which are used in describing the physical phenomena of heat.

7. When a body receives or loses heat, it generally suffers a change in its dimensions, the increase of heat being usually attended with an increase of volume, and the diminution of heat with a diminution of volume. This enlargement of volume due to the accession of heat is called *expansion*, or *dilatation*, and the diminution of volume attending the loss of heat is called *contraction*. There are, however, certain exceptional cases in which heat, whether received or lost, is attended with no change of volume, and others in which changes take place the reverse of those just mentioned ; that is to say, where an accession of heat is accompanied by a diminution of volume, and a loss of heat with an increase of volume.

8. If heat be imparted in sufficient quantity to a solid body, it will pass into the liquid state. Thus, ice or lead, being solid, will become liquid by receiving a sufficient accession of heat. This change is called *fusion* or *liquefaction*. If heat be extracted in sufficient quantity from a body in the liquid state, it will pass into the solid state. Thus, water or molten lead losing heat in sufficient quantity will become solid. This change is called *congelation* or *solidification* ; the former term being applied to substances which are under ordinary circumstances liquid, and the latter to those that are usually solid.

If heat be imparted in sufficient quantity to a body in the liquid state, it will pass into the state of vapour. Thus, water being heated sufficiently will pass into the form of steam. This change is called *vaporisation*. If a body in the state of vapour lose heat in sufficient quantity, it will pass into the liquid state. Thus, if a certain quantity of heat be abstracted from steam, it will become water. This change is called *condensation* ; because, in passing from the vaporous to the liquid state, the body always undergoes a very considerable diminution of volume, and therefore becomes condensed.

9. Heat, when imparted to bodies in a certain quantity, will in some cases render them luminous. Thus, a piece of iron, heated to a certain degree, emits red light ; we then say that the body is *red hot*. This luminous state, which is depending on the accession of heat, is called *incandescence*.

The more intense the heat is which is imparted to an incandescent body, the more *white* will be the light which it emits. When it first becomes luminous, it emits a dusky red light. The redness becomes brighter as the heat is augmented, until at length, when the heat becomes extremely intense, it emits a white light resembling solar light. A bar of iron submitted to the action of a furnace will exhibit a succession of phenomena illustrative of this.

10. Certain bodies, when surrounded by atmospheric air, being heated to a certain degree, will enter into chemical combination with the oxygen gas which forms one of the constituents of the atmosphere. This combination will be attended with a large development of heat, which is accompanied usually by incandescence and flame. This phenomenon is called *combustion*, and bodies which are susceptible of this effect are called *combustible* bodies. The flame, which is one of the effects of combustion, is gas rendered incandescent by heat.

11. When heat is communicated to any part of a body, the temperature of that part of the body is momentarily raised above the general temperature of the body. This excess of heat, however, is gradually transmitted from particle to particle throughout the whole mass, until it becomes uniformly diffused and the temperature of the body becomes equalised.

The quality in virtue of which heat is transmitted from particle to particle throughout the volume of a body, is called *thermal conductivity*.

Bodies have the quality of conductivity in different degrees ; those being called good conductors in which any inequality of temperature is quickly equalised, the excess of heat being transmitted with great promptitude and facility from particle to particle. Those in which it passes more slowly and imperfectly through the dimensions of a body, and in which, therefore, the equilibrium of temperature is more slowly established, are called imperfect conductors. Bodies in which the excess of heat fails to be transmitted from particle to particle before it has been dissipated in other ways are called non-conductors.

The metals in general are good conductors, but different metals have different degrees of conductivity. The earths and woods are bad conductors, and soft, porous, and spongy substances still worse.

12. Heat is propagated from bodies by *radiation* in the same manner and according to nearly the same laws as those which govern the radiation of light. Thus it proceeds in straight lines from the points whence it emanates, diverging in every direction, *these lines being called thermal rays*.

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Certain bodies are pervious to the rays of heat, just as glass and other transparent media are pervious to the rays of light. They are called *diathermanous* bodies. Thus atmospheric air and gaseous bodies in general are more or less diathermanous.

The rays of heat are reflected and refracted according to the same laws as those of light. They are collected into foci by spherical mirrors and lenses, they are polarised both by reflection and refraction, and are subject to all the phenomena of double refraction by certain crystals in a manner analogous to that which takes place in relation to the rays of light.

Bodies are diathermanous in different degrees. Imperfectly diathermanous bodies transmit some of the rays of heat which impinge on them, and absorb others ; the portions which they absorb raising their temperature, but those which they transmit not affecting their temperature.

The surfaces of bodies reflect heat in different degrees ; those rays which they do not reflect they absorb. The degrees of transmission, absorption, and reflection vary with the nature of the body and the state of its surface with respect to smoothness, roughness, or colour.

Rays of heat, like those of light, are differently refrangible.

13. The term heat is used in different senses ; first, to express our own sensations when we are surrounded by a hot medium or touch a heated body ; secondly, to express the quality of the body by which this sensation is produced ; and thirdly, to express the physical cause, whatever it be, to which the phenomena are due.

Notwithstanding these different senses of the same term, no confusion or obscurity arises in its use, the particular sense in which it is applied being generally evident. The term *caloric* has formerly been much used in a special sense, viz., expressing the physical agency to which the effects of heat are due.

14. Two hypotheses have been proposed to explain the phenomena of heat. The first regards heat as an extremely subtle fluid, pervading all space, entering into combination in various proportions and quantities with bodies, and producing by this combination the effects of expansion, fusion, vaporisation, and all the other phenomena above mentioned. The second hypothesis regards it as some kind of motion either of the constituent molecules of the body, or of a subtle fluid, called *Æther*, which penetrates all bodies. The theory of heat according to the most recent views will be fully explained further on, but in the first portion of this work the general effects of heat will be *stated independently* of any hypothesis.

CHAPTER II.

THERMOMETRY.

15. **Definition of temperature.**—The state of a body considered with reference to its power of communicating heat to other bodies is called its *temperature*. The state of a body with reference to heat generally may be designated as its *thermal state*, and when bodies are placed in communication with reference to heat, they may be said to be in *thermal communication*. Now whenever two bodies are in thermal communication, and one body loses heat while the other gains heat, the body which loses heat is said to have a higher temperature than the body which receives heat from it.

It follows from this, that two bodies have equal temperatures if neither of them loses or gains heat, when they are placed in thermal communication. Such two bodies are also said to be in *thermal equilibrium*.

16. **Measures of temperature.**—It will be seen at once that the statements contained in the preceding article give us a means of comparing the temperature of any two bodies, so as to determine which has the higher temperature, and at the same time a test of the equality of temperature which is independent of the nature of the bodies tested. But we have as yet no means of estimating numerically the difference between two temperatures with reference to a definite unit, so as to be able to assert that a certain temperature, for example, is exactly half-way between two other temperatures.

All measurement of temperature rests on the following *Law of Equal Temperatures*:—

Bodies whose temperatures are equal to that of the same body have themselves equal temperatures.

This law expresses the fact that if a piece of iron when plunged into a vessel of water is in thermal equilibrium with the water, and if the same piece of iron, without altering its temperature, is transferred to a vessel of oil, and is found to be in thermal equilibrium with the oil, then if the oil and water were put into the same vessel they would themselves be in thermal equilibrium, and the same would be true of any other three substances.

Of all the various effects of heat, that which is best adapted

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to indicate and measure temperature is dilatation and contraction. The same body always has the same volume at the same temperature, and always suffers the same change of volume with the same change of temperature.

Since the volume and change of volume admit of the most exact measurement and of the most precise numerical expression, they become the means of submitting differences of temperature to numerical measure and expression.

The instruments employed for the measurement of temperature are called *Thermometers*. Certain kinds of such instruments, mostly confined to the measurement of high temperatures, and to be described hereafter, are called *Pyrometers*.

If we take an instrument of this kind, such as the common mercurial thermometer, which will be described immediately, and bring it into intimate contact with different bodies, by plunging it into liquids, or inserting it into holes made in solid bodies, we find that the mercury in the tube rises or falls till it has reached a certain point, at which it remains stationary. We then know that the thermometer is neither becoming hotter nor colder, but is in thermal equilibrium with the surrounding body. It follows from this, by the law of equal temperatures, that the temperature of the body is the same as that of the thermometer, and the temperature of the thermometer itself is known from the height at which the mercury stands in the tube. Hence the *reading*, as it is called, of the thermometer—that is, the number of degrees indicated on the scale by the top of the mercury in the tube—informs us of the temperature of the surrounding substance, as well as of that of the mercury in the thermometer. It is in this way that the thermometer may be used to compare the temperature of any two bodies at the same time or at different times.

17. **The mercurial thermometer.**—Although all bodies are susceptible of dilatation and contraction by change of temperature, they are not equally convenient for the purpose of measuring temperatures. For reasons which will become apparent hereafter, the most available thermometric substance for general purposes is mercury. The mercurial thermometer consists of a capillary tube of glass, at one end of which a thin spherical or cylindrical bulb is blown, the bulb and a part of the tube being filled with mercury.

When such an instrument is exposed to an increase of temperature, the glass and mercury will both expand. If they expanded in the same proportion, the capacity of the bulb and tube would be enlarged in the same proportion as the mercury

contained in them, and, consequently, the column of mercury in the tube would neither rise nor fall, since the enlargement of its volume would be exactly equal to the enlargement of the capacity of the bulb and tube. If, however, the expansion of the bulb and tube be different from that of the mercury, the column in the tube will, after expansion, stand higher or lower than before, according as the expansion of the mercury is greater or less than the expansion of the bulb and tube.

It is found that the expansion of mercury is greater than that of glass in the proportion of nearly 20 to 1, and, consequently, the capacity of the bulb and tube will be less enlarged than the volume of the mercury contained in them in the proportion of nearly 1 to 20; hence, for the reason above stated, every elevation of temperature by which the mercury and tube would be affected will cause the column of mercury to rise in the tube, and every diminution of temperature will cause it to fall.

The space through which the mercury will rise in the tube by a given increase of temperature will be greater or less according to the proportion which the tube bears to the capacity of the bulb. The smaller the proportion the tube bears to the capacity of the bulb, the greater will be the elevation of the column produced by a given increase of temperature; for a given increase of temperature will produce a definite increase of volume in the mercury, and this increase of volume will fill a greater space in the tube in proportion to the smallness of the bore of the tube compared with the capacity of the bulb.

Such an instrument, without other appendages or preparation, would merely indicate such changes of temperature in a given place as would be sufficient to produce visible changes in the elevation of the column of mercury contained in the tube. To render it useful for the purposes of science and art, and in domestic economy, various precautions are necessary, which have for their object to render the indications of different thermometers comparable with each other, and to supply means for exact numerical measurement of the changes of temperature.

18. The construction of the mercurial thermometer.—The first condition to be fulfilled is that the mercury with which the tube is filled shall be as pure as possible, and freed from moisture and air by the same means as have been already explained in the case of the barometer ('HYDROSTATICS,' p. 134).

In the selection of the tube it is necessary that it be capillary, that is to say, a tube having an extremely small bore, and that the bore should be of uniform magnitude throughout its entire

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length. The smallness of the bore is essential to the sensibility of the instrument, as already explained ; and its uniformity is necessary in order that the same change of volume of the mercury should correspond to the same length of the column in every part of the tube.

The uniformity of the bore of the tube may be tested by letting into it a small drop of mercury, sufficient to fill about a third of an inch of the tube. Let this be made to fall gradually through the entire length of the tube, stopping its motion at intervals, and let the space it occupies at different parts of the tube be measured. If this space be everywhere approximately the same, the bore is uniform ; if not, the tube must be rejected.

The bulb, whether spherical or cylindrical, can be formed upon the end of the tube by the ordinary process of glass blowing. The sensibility of the thermometer requires that the capacity of the bulb should bear a large proportion to the calibre of the tube. If, however, the capacity of the bulb be considerable, the quantity of mercury it contains may be so great that it will not be affected by the temperature of the surrounding medium with sufficient promptitude.

A cylindrical bulb of the same capacity will be more readily affected by the temperature of the surrounding medium than a spherical bulb, since it will expose a greater surface, although it contains an equal quantity of mercury.

The glass of which the bulb is formed should be as thin as is compatible with the necessary strength, in order that the heat may pass more freely from the external medium to the mercury.

The tube to be filled is represented in *fig. 1*. *c* is a reservoir formed at the top for the purpose of filling it, which is to be afterwards detached. Let the tube be first dried by holding it over the flame of a spirit-lamp, so as to

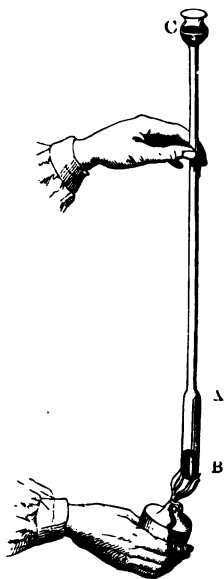


Fig. 1.

evaporate and expel any moisture which may be attached to the inner surface of the glass. To fill it, let a quantity of purified mercury be poured into the reservoir *c*. This will not

fall through the bore, partly being prevented by the air included in the reservoir *A B* and in the tube, and partly because the mercury requires a certain pressure from without to enter so narrow a tube. To expel the air, and cause the mercury to take its place, let the tube be placed in an inclined position over a charcoal fire or the flame of a spirit-lamp, so that the air shall be heated. When heated the air will expand, force itself in bubbles through the mercury in *c*, and escape into the atmosphere. This will continue until nearly all the air in the bulb and tube has been expelled. After the interior of the tube and bulb has been allowed to become cool again, the pressure of the atmosphere acting on the mercury in *c* will then force it through the tube into the bulb *A B*, which, as well as the entire length of the tube, it will ultimately fill, the operation of alternately heating and cooling being repeated a requisite number of times. If a sufficient quantity of mercury be supplied to the reservoir *c*, the bulb *A B*, the tube, and a part of the reservoir *c*, will be filled with mercury after all the air has been expelled.

When this has been accomplished, let the tube be removed from the source of heat, and allowed gradually to cool. A file applied at *c*, where the top of the tube is joined to the superior reservoir, detaches that reservoir from the tube, which remains with the bulb *A B* completely filled with mercury.

In this state the instrument would give no indication of change of temperature, no space being left for exhibiting the play of the mercury by dilatation and contraction.

To obtain space for this, let the bulb *A B* be exposed to a temperature higher than any which the instrument is intended to indicate. The mercury dilating will then overflow, and will continue to overflow until it acquires the extreme temperature to which it is exposed.

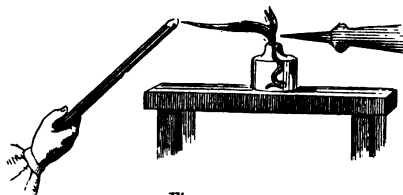


Fig. 2.

Let now the jet of a flame be directed by a blow-pipe upon *c* so as to close that end, *fig. 2*. The instrument being then allowed to cool, the mercurial column will subside, until the mercury

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has assumed that state which corresponds to the temperature of the air surrounding the instrument.

19. **The graduation of the thermometer.**—The variation of the height of the mercurial column in such a tube will in all cases correspond with the changes of temperature incidental to the surrounding medium ; but, in order that it may supply a numerical expression and measure of such changes, a scale must be attached to the tube, by which the variations of the column may be indicated, and the divisions of the units of such scale must correspond to some known change of temperature. It is evident that such a scale, like all other standards for the numerical measure of physical effects, must be to some extent arbitrary. We accordingly find different scales and different thermometric units prevailing in different countries, and even in the same country at different times.

Whatever thermometric unit be adopted, it is necessary that two standard temperatures be selected, to which the mercury can be reduced at the times and places where thermometers may be required to be constructed or verified. The instrument being exposed to these two temperatures, the points at which the mercurial column stands are marked upon the scale. The space upon the scale between these points is thus divided into a certain number of equal parts, which are called degrees, these degrees being the thermometric units. The same divisions are then continued upon the scale above the higher and below the lower standard point, and such divisions may be continued indefinitely. The scale is then complete.

In this process, the number of equal parts into which the space between the standard points is divided is altogether arbitrary.

It now remains to number the scale ; and, for this purpose, a zero point must be selected. If there existed a minor limit to temperature,—a temperature below which no body could possibly fall,—then such a temperature would supply a natural absolute thermometric zero, and the scale might be numbered upwards from it. In that case, although the thermometric unit would still remain arbitrary, the zero of the scale would not be so. But no such natural thermometric zero exists ; as far as experimental research extends, there is no natural limit either to the increase or diminution of temperature. The reader will, however, find as he goes on, that a certain very low temperature has for valid reasons been adopted as the absolute zero of temperature.

20. **The fixed points of the scale.**—It follows from what

has been said that the zero of the thermometric scale, like the thermometric scale itself, must be arbitrary.

Thermal phenomena present great varieties of standard temperatures, by which thermometric scales may be established, and which may serve equally as terms of temperature for the purpose of distinguishing the indications of thermometers constructed at different times and places. Thus, the temperatures at which all solid bodies fuse, and those at which all liquids congeal, are fixed. For different bodies these are different, but always the same for the same body. In like manner, the temperatures at which all liquids boil under a given pressure are invariable for the same liquids, though different for different liquids.

Now any two of these various temperatures naturally fixed might be taken as the thermometric standards, the choice being altogether arbitrary. Thus, it appears that the arithmetical division of the scale, and consequently the thermometric unit, the position of its zero, and, in fine, the standard temperatures by which alone the indication of different thermometers can be rendered comparable, are severally arbitrary. Unanimity, nevertheless, has prevailed in the selection of standard temperatures. The temperature at which ice melts, and that at which pure water boils (or more correctly the temperature of steam at an atmospheric pressure of 29·922 inches of mercury in the latitude of 45°, at the sea-level, corresponding at *London* to a pressure of 29·905 inches of mercury, reduced to the freezing point), have been adopted as the two temperatures with reference to which thermometric scales are constructed.

21. Experimental determination of the fixed points.—

The bulb and tube, as already described, being filled with pure mercury, the instrument is immersed successively in melting ice, and steam issuing from boiling water, and the points at which the mercurial column stands in each case are marked upon the tube or upon a blank scale attached to it. The former is the *freezing point*, the latter the *boiling point*.

To determine the *freezing point*, the bulb and tube are

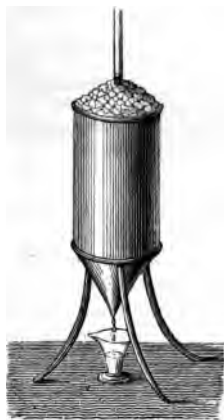


Fig. 3.

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placed in a vessel of sufficient depth, such as that shown in *fig. 3*, and surrounded with pounded ice, a hole being left in the bottom, from which the water proceeding from the fusion of the ice is discharged. By this arrangement, the entire quantity of mercury included in the bulb and tube must necessarily be reduced to the exact temperature of melting ice. When the summit of the mercurial column in the tube is observed to become stationary, its position is marked on the glass by a

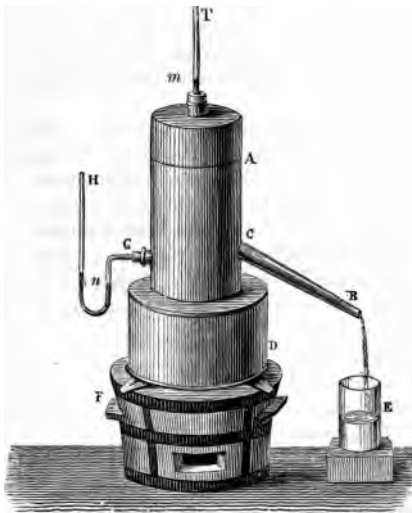


Fig. 4.

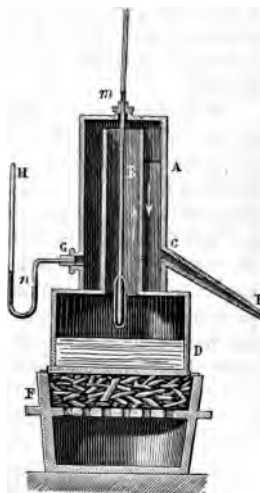


Fig. 5.

diamond point. This will be, therefore, the freezing point of the thermometer.

To determine the boiling point, the thermometer is in like manner immersed in a reservoir of steam, proceeding from boiling water when the barometer stands at 29.905 inches.

The manner in which this process is conducted is shown in *fig. 4*, where D is the boiler placed over a charcoal furnace F, shown in section in *fig. 5*. From the top of the boiler a tube proceeds, open at the top, which is enveloped by another, A, closed at the top and soldered at the bottom to the top of the boiler. In the external tube or *jacket* A there are three openings, in one of which, m, the tube of the thermometer T is inserted. In another, a mercurial gauge G H, and, in the third a discharge tube, C B is inserted. When the water boils, the steam rises,

surrounding the bulb and tube, and, descending between the two tubes, issues from the discharge pipe B. If the steam be generated too rapidly in the boiler, it will press on the mercury in the gauge, which will then stand at a higher level *n* in the ascending than in the descending leg. In that case, the pressure of the steam will be greater than that of the atmosphere, and the force of the furnace must be moderated until the level of the mercury in the two legs of the gauge coincide, when the pressure of the steam will be exactly equal to that of the atmosphere.

22. The barometrical correction of the boiling point.—

It will be explained hereafter that the temperature of a boiling liquid rises or falls with every increase or decrease of the height of the barometric column. This is the reason why it is necessary (as in Article 20), that in fixing the conventional standard of the boiling point, the corresponding height of the barometer must be stated at the same time, such conventional height being usually the average height of the barometer at the level of the sea. It follows from this, that if the boiling-point of any thermometer be experimentally determined in London at any time when the barometric column is less or greater than the standard height of 29·905 inches, a correction will have to be applied, the nature of which will appear from an inspection of the following table :—

Temperature of steam at different pressures.

Temperature	Pressure in Inches of Mercury at 32° Fahr.	Temperature	Pressure in Inches of Mercury at 32° Fahr.
211·0	29·315	212·0	29·905
211·1	29·374	212·1	29·964
211·2	29·432	212·2	30·024
211·3	29·491	212·3	30·083
211·4	29·550	212·4	30·143
211·5	29·609	212·5	30·203
211·6	29·668	212·6	30·263
211·7	29·727	212·7	30·323
211·8	29·786	212·8	30·384
211·9	29·845	212·9	30·444

Thus, for example, if a thermometer were immersed in steam, when the barometer indicates a pressure of 30·384 inches, the top of the mercury should be marked 212·8°, and not 212°, and similarly for other pressures. This correction is treated more in detail in Article 29.

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23. **Different thermometric scales.**— Very little unanimity has prevailed either as respects the unit or the zero of the thermometric scale. In England, Holland, North America, and the British Colonies, the interval between the freezing and boiling points is divided into 180 equal parts, each part representing the thermometric unit. The scale is continued by equal divisions above the boiling and below the freezing points. The zero is placed at the thirty-second division below the freezing point ; so that, on this scale, the freezing point is 32° , and the boiling point $32^{\circ} + 180 = 212^{\circ}$. This scale is known as *Fahrenheit's*, and was adopted about 1724.

The reason for fixing the zero of the scale at 32° below the freezing point was, that that point indicated a temperature which was at that time believed to be the natural zero of temperature, or the greatest degree of cold which could exist, being the most intense cold which had been observed in Iceland. When the instrument stood at the greatest cold of Iceland, or 0 degree, it was computed to contain 11,124 equal parts of mercury, which when plunged in melting snow, expanded to 11,156 parts ; hence the intermediate space was divided into 32 equal portions, and 32 was taken as the freezing point of water. When the thermometer was plunged in boiling water, the mercury was expanded to 11,336, and therefore 212° was marked at the boiling point of that liquid. Thus, in practice, Fahrenheit determined the divisions of his scale from two fixed points—the freezing and boiling of water ; while in theory the expansion of a given portion of mercury was determined.

We shall see hereafter that much lower temperatures, natural and artificial, have been since observed. Moreover, the division of the interval between the freezing and boiling points into 180 equal parts was founded upon an inexact supposition or experimental determination connected with the dilatation of mercury.

The divisions of this scale are continued in the same manner below zero, such divisions being considered negative, and expressed by the negative sign prefixed to them. Thus, $+32^{\circ}$ signifies 32° above zero, but -32° signifies 32° below zero.

In France, Sweden, and some other parts of Europe, the *centigrade* scale prevails.

In this scale the interval between the freezing and boiling points is divided in 100 equal parts, and the zero is placed at the freezing point.

In Germany *Reaumur's* scale is used, in which the interval between the freezing and boiling points is divided into eighty equal parts, the zero being placed at the freezing point.

24. Comparative table of the scales.—Since the numbers of degrees into which the interval between the freezing and boiling point is divided on the three scales are 180, 100, and 80 respectively, it follows that 9° Fahrenheit, 5° centigrade, and 4° Reaumur are represented by equal lengths. Hence are inferred the following rules :—

I. To reduce any number of Fahrenheit degrees to an equivalent number of centigrade or Reaumur degrees, divide by 9, and multiply by 5 for centigrade, and by 4 for Reaumur.

II. To reduce any number of centigrade degrees to an equivalent number of Fahrenheit or Reaumur, divide by 5, and multiply by 9 for Fahrenheit, and by 4 for Reaumur.

III. To reduce any number of Reaumur degrees to an equivalent number of Fahrenheit or centigrade, divide by 4, and multiply by 9 for Fahrenheit, and by 5 for centigrade.

By these rules we may find for any given number of degrees of one scale the corresponding equivalent number of degrees of the two other scales. But in order to convert the *reading* of any of the three scales into the corresponding reading of the two others, we must employ the following formulæ, in which t is the number of degrees read off on any thermometer, and F, C, R, stand for the scales of Fahrenheit, Celsius (centigrade), and Reaumur, respectively :

$$\begin{array}{rclcl} \text{F.} & & \text{C.} & & \text{R.} \\ t & = & \frac{5}{9}(t - 32) & = & \frac{4}{9}(t - 32) \\ \frac{9}{5}t + 32 & = & t & = & \frac{4}{5}t \\ \frac{9}{4}t + 32 & = & \frac{5}{4}t & = & t \end{array}$$

By the following table, computed by the above formulæ, the corresponding temperatures on these scales may be found :—

Cent.	Reau.	Fahr.	Cent.	Reau.	Fahr.	Cent.	Reau.	Fahr.	Cent.	Reau.	Fahr.
100	80°	212°	82	65°6	179°6	64	51°2	147°2	46	36°8	114°8
99	79°2	210°2	81	64°8	177°8	63	50°4	145°4	45	36°	113°
98	78°4	208°4	80	64°	176°	62	49°6	143°6	44	35°2	111°2
97	77°6	206°6	79	63°2	174°2	61	48°8	141°8	43	34°4	109°4
96	76°8	204°8	78	62°4	172°4	60	48°	140°	42	33°6	107°6
95	76°	203°	77	61°6	170°6	59	47°2	138°2	41	32°8	105°8
94	75°2	201°2	76	60°8	168°8	58	46°4	136°4	40	32°	104°
93	74°4	199°4	75	60°2	167°	57	45°6	134°6	39	31°2	102°2
92	73°6	197°6	74	59°4	165°2	56	44°8	132°8	38	30°4	100°4
91	72°8	195°8	73	58°6	163°4	55	44°	131°	37	29°6	98°6
90	72°	194°	72	57°8	161°6	54	43°2	129°2	36	28°8	96°8
89	71°2	192°2	71	56°	159°8	53	42°4	127°4	35	28°	95°
88	70°4	190°4	70	56°	158°	52	41°6	125°6	34	27°2	93°2
87	69°6	188°6	69	55°2	156°2	51	40°8	123°8	33	26°4	91°4
86	68°8	186°8	68	54°4	154°4	50	40°	122°	32	25°6	89°6
85	68°	185°	67	53°6	152°6	49	39°2	120°2	31	24°8	87°8
84	67°2	183°2	66	52°8	150°8	48	38°4	118°4	30	24°	86°
83	66°4	181°4	65	52°	149°	47	37°6	116°6	29	23°2	84°2

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Cent.	Reau.	Fahr.	Cent.	Reau.	Fahr.	Cent.	Reau.	Fahr.	Cent.	Reau.	Fahr.
28	22.4	82.4	10	8	50	-7	-5.6	19.4	-24	-19.2	-11.2
27	21.6	80.6	9	7.2	48.2	8	6.4	17.6	25	20	13
26	20.8	78.8	8	6.4	46.4	9	7.2	15.8	26	20.8	14.8
25	20	77	7	5.6	44.6	10	8	14	27	21.6	16.6
24	19.2	75.2	6	4.8	42.8	11	8.8	12.2	28	22.4	18.4
23	18.4	73.4	5	4	41	12	9.6	10.4	29	23.2	20.2
22	17.6	71.6	4	3.2	39.2	13	10.4	8.6	30	24	22
21	16.8	69.8	3	2.4	37.4	14	11.2	6.8	31	24.8	23.8
20	16	68	2	1.6	35.6	15	12	5	32	25.6	25.6
19	15.2	66.2	1	0.8	33.8	16	12.8	3.2	33	26.4	27.4
18	14.4	64.4	0	0	32	17	13.6	1.4	34	27.2	29.2
17	13.6	62.6	-1	-0.8	30.2	18	14.4	-0.4	35	28	31
16	12.8	60.8	2	1.6	28.4	19	15.2	2.2	36	28.8	32.8
15	12	59	3	2.4	26.6	20	16	4	37	29.6	34.6
14	11.2	57.2	4	3.2	24.8	21	16.8	5.8	38	30.4	36.4
13	10.4	55.4	5	4	23	22	17.6	7.6	39	31.2	38.2
12	9.6	53.6	6	4.8	21.2	23	18.4	9.4	40	32	40
11	8.8	51.8									

The centigrade scale has gradually been more and more introduced into scientific works, and will chiefly be made use of in the present treatise.

25. Precautions in the construction of a thermometer.—

Various points of importance must be attended to, besides the barometric correction, in order to render a mercurial thermometer a trustworthy instrument for measuring temperature. In the first instance, in adopting the dilatation of mercury as a measure of temperature, it is assumed that equal dilatations of this fluid are produced by equal increments of heat. Now, although it is certain that to raise a given quantity of mercury from the freezing to the boiling point will always require the same quantity of heat, it does not follow that equal increments of volume will correspond to equal increments of heat throughout the whole extent of the thermometric scale. Thus, although the same quantity of heat must always be imparted to the mercury contained in the tube to raise it from 0° to 100° , it may happen that more or less heat may be required to raise it from 0° to 10° than from 90° to 100° . In other words, the dilatation produced by equal increments of heat, in different parts of the scale, might be variable. Experiments conducted, however, under all the conditions necessary to ensure accurate results, have proved that mercury is almost uniformly dilated between the freezing and boiling points, or that equal increments of heat imparted to it produce equal increments of volume. The same nearly uniform dilatation prevails to a considerable extent of the scale above the boiling and below the freezing points; but at extreme temperatures this uniformity of expansion ceases, as will be more fully explained hereafter.

Mercury possesses, besides this pretty uniform dilatation within a certain range of temperature, several thermal qualities which render it a suitable and convenient fluid for common thermometers. It is highly sensitive to change of temperature, dilating with promptitude by the same increments of heat with great regularity and through a considerable range of temperature. It will be shown hereafter that a smaller quantity of heat produces in it a greater dilatation than in most other liquids. It freezes at a very low and boils at a very high temperature. At the temperatures which are not near these extreme limits, it expands and contracts with considerable uniformity.

The freezing point of mercury being about -39° , or 39° below zero on the centigrade scale, and its boiling point $+350^{\circ}$, the mercurial thermometer may thus be employed for a very large range of temperature. In general the range of the scale of thermometers is determined by the purpose to which they are to be applied. Thus, thermometers intended to indicate the temperature of dwelling-houses need not range above or below the extreme temperatures of the air, and the scale does not usually extend much below the freezing point nor above 100° ; and thus the sensitiveness of the instrument may be increased, since a considerable length of the tube may represent a limited range of scale.

26. Change of zero-point.—The next point to which attention must be paid is due to a gradual change in the glass-tube of the thermometer. It has been found that, from some physical causes which are not yet quite satisfactorily explained, the bulbs of thermometers are liable to a change of magnitude after the lapse of a certain time. It follows from this that a thermometer, though accurately graduated when first made, may become at a later period erroneous in its indications; for a diminution of the capacity of the bulb would cause the standard points and all other temperatures to be raised upon the scale, while an enlargement of the bulb or stem would cause the standard points to be lowered.

The phenomena actually observed are of the following nature:—*First*, if a thermometer has already its standard points *correctly* marked, and is first plunged in boiling water and immediately afterwards in melting ice, the top of the mercury will fall and remain stationary *below* the original zero-point by a fraction of a degree, and the instrument will not recover the true reading of the zero-point until a week or two afterwards. In this case the bulb and stem have expanded by the immersion in boiling water, but they do not immediately contract to their original

volume when cooled again by the ice. It appears that time is required for the return to the previous state, and it follows that the zero-point of the scale should always be determined previous to the determination of the boiling-point. *Second*, the pressure of the atmosphere appears to have some definite influence on the internal capacity of thermometers. Systematic experiments made on this subject by the editor of this treatise have proved that the capacity of thermometers is increased in a vacuum, and that the reading of a thermometer under the receiver of an air-pump is lower by a constant quantity than the reading of the same thermometer when under the pressure of the air, the temperature being in both cases the same. A vacuum-correction has therefore to be applied to the indications of a thermometer when it is used under a diminished atmospheric pressure. *Third*, either the prolonged effect of the atmospheric pressure upon the thin glass of the bulbs of thermometers, or the fact that the equilibrium of the particles of the glass, after having been greatly disturbed by the operation of boiling the mercury, can only be very gradually restored after a lapse of time, seems to be the cause of a more permanent displacement of the zero-point, due to a steady diminution of the internal capacity. Thus, if a thermometer which has been correctly graduated, after some years, be tested, the zero-point will be found not at 0° , but a fraction of a degree above 0° .

It follows from these facts that whenever a thermometer is to be used for purposes requiring much precision, it ought to be verified by comparison with well-constructed standard instruments, or its fixed points should be again determined independently.

27. Standard thermometers.—A thermometer, having once been carefully graduated, may be used as a standard instrument, either for graduating other thermometers, or for determining any errors in their graduation. To graduate a thermometer by means of such a standard, it is only necessary to expose the two instruments to the same varying temperatures, and to mark upon the blank scale of that which is to be graduated two points corresponding to any two temperatures shown by the standard thermometer, and then to divide the scale accordingly.

Thus, for example, if the two instruments be immersed in warm water, and the column of the standard thermometer be observed to indicate the temperature of 80° , let the point at which the mercury stands in the other thermometer be marked upon its scale.

Let the two instruments be then immersed in cold water, and

let us suppose that the standard thermometer indicates 10° . Let the point at which the instrument to be graduated stands be then marked. Let the intervals of the scale between these two points, thus corresponding to the temperatures of 10° and 80° , be divided into seventy equal parts; each part will be a degree in the scale, which may be continued by like divisions above 80° and below 10° .

- In accurate thermometers the scale is marked on the stem itself. It cannot be displaced, and as glass is very inexpandible, the length of the scale remains nearly the same. The graduation is usually effected in the following manner:—The stem is covered with a thin layer of wax, and the divisions, as well as the corresponding numbers, are marked with a steel point. The thermometer is then exposed for about ten minutes to the vapours of hydrofluoric acid, which has the property of attacking glass. The glass is thus etched where the wax has been removed, that is, upon the marked divisions and numbers.

28. **Calibration.**—It is further necessary in a good thermometer that the tube be *calibrated*. The bore of a glass-tube is usually not everywhere throughout its length of uniform width. It follows that if the distance between the two fixed points were divided into equal portions of length, the degrees would not correspond to the same amount of dilatation of the mercury where the tube is narrow as where it is wide. To calibrate a thermometer means measuring its width at short intervals all along its length. This is done by detaching, before the scale is graduated, a small quantity of mercury from the remainder, and moving it along the tube. If the length of this little column remains the same as it passes along the tube, the bore is uniform; but if not, that is, if the column is in one place shorter or longer than in another place, the divisions of the scale will have to be made respectively shorter or longer than in other portions of the scale.

29. **Methods of ascertaining the exact boiling point.**—The *normal* boiling temperature of water all nations have tacitly agreed to fix under a normal barometric pressure of 29.922 inches of mercury, having the temperature of melting ice, in the latitude of 45° , and at the sea-level. If the atmospheric pressure at the time or place of graduating a thermometer does not equal this, the boiling temperature will be higher or lower according as the pressure is greater or less. Hence a reading must be taken of a trustworthy barometer, which must also be corrected for errors (see 'HYDROSTATICS,' page 134, etc.) and temperature, and reduced for latitude, in order to compare the actual

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atmospheric pressure at the time with the assumed normal pressure.

The Commissioners appointed by the British Government to construct standard weights and measures, decided that the normal boiling point, 212° , on the thermometer should represent the temperature of steam generated under an atmospheric pressure equal in inches of mercury, at the temperature of freezing water, to

$$29\cdot922 + (\cos 2 \times \text{latitude} \times \cdot0766) + (\cdot00000179 \times \text{height in feet above the sea-level}).$$

Hence at London, lat. $51^{\circ} 30' \text{ N.}$, we deduce $29\cdot905$ as the barometric pressure representing the normal boiling point of water,—the trifling correction due to height being neglected. If then, in the latitude of London, the barometric pressure, at the time of fixing the boiling point, be not $29\cdot905$ inches, that point will be higher if the pressure is higher, and lower if the pressure is lower than $29\cdot905$ inches. Near the sea-level about $0\cdot59$ inch of such difference is equivalent to 1° Fahrenheit in the boiling point, as seen from the little table in Article 22. If the pressure in London is higher or lower than the range of that table, we may proceed as follows.

Suppose the pressure to be $30\cdot785$; then we have the following little calculation to perform :

Observed pressure	.	.	.	$30\cdot785$
Normal	„	.	.	$29\cdot905$
Difference	.	.	.	<u>$\cdot880$</u>
$0\cdot59 : 0\cdot88 :: 1^{\circ} : x$				
$x = 1^{\circ}\cdot5,$				

that is, the water boils at $1^{\circ}\cdot5$ above the normal temperature, so that in this case the normal temperature to be placed on the scale, viz. 212° , must be $1^{\circ}\cdot5$ lower than the mark made on the tube at the height at which the mercury was stationary under the actual circumstances, while that mark will denote a temperature of $213^{\circ}\cdot5$.

For places at any other latitude, and altitude above the level of the sea, the true boiling point may be found with the help of the following two small tables, and the rule :

Multiply the observed atmospheric pressure by the factor due to latitude in Table I., and with the result seek the temperature in Table II.

Table I.

Table II.

Latitude	Factor	Pressure	Temperature of Vapour	Pressure	Temperature of Vapour
Degrees		Inches	Degrees	Inches	Degrees
0	0.99735	14.934	179	22.036	197
5	0.99739	15.271	180	22.501	198
10	0.99751	15.614	181	22.974	199
15	0.99770	15.963	182	23.456	200
20	0.99797	16.318	183	23.946	201
25	0.99830	16.680	184	24.445	202
30	0.99868	17.049	185	24.952	203
35	0.99910	17.425	186	25.468	204
40	0.99954	17.808	187	25.993	205
45	1.00000	18.197	188	26.527	206
50	1.00046	18.594	189	27.070	207
55	1.00090	18.998	190	27.623	208
60	1.00132	19.409	191	28.185	209
65	1.00170	19.828	192	28.756	210
70	1.00203	20.254	193	29.335	211
75	1.00230	20.688	194	29.922	212
80	1.00249	21.129	195	30.515	213
		21.578	196	31.115	214

When the pressure does not exactly correspond to those given in the Table II., take the difference between it and the next less pressure in the table and divide this difference by the next less and next greater pressures. The quotient will be the decimals to be added to the degree opposite to the next less pressure.

Thus, for a pressure of 23.214 inches, required the temperature.

Given	23.214	Next greater	23.456
	<u>22.974</u>	Next less	<u>22.974</u>
Differences	.240		.482

$$\text{and } \frac{.240}{.482} = .5$$

Temperature opposite next less	.	199.0
Add	.	<u>.5</u>
Temperature required	.	<u>199.5</u>

Complete example.—In Liverpool, lat. 53° 50' N., the barometer reading 29.876 inches, its attached thermometer 55° (see further on, on the temperature-correction of barometers), and the correction of the instrument being +.015, including index error, capillarity and capacity (see 'HYDROSTATICS,' page 133, Article 104, and page 136, Article 106), what temperature should be assigned to the boiling point marked on the thermometer?

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Observed barometer . . .	29·876
Correction	+ '015
	<u>29·891</u>
Correction for temperature . . .	- '074
Reduced reading	29·817
Factor from Table I.	1·00077
	<u>208719</u>
	208719
	<u>29817</u>
Corrected for latitude	29·83995909 = 29·84 inches.

In Table II., 29·84 gives a temperature, after completing the above interpolation, of $211^{\circ}86$.

30. **Self-registering thermometers.**—It is sometimes needed, in the absence of an observer, to ascertain the variations which have taken place in a thermometer, or rather the

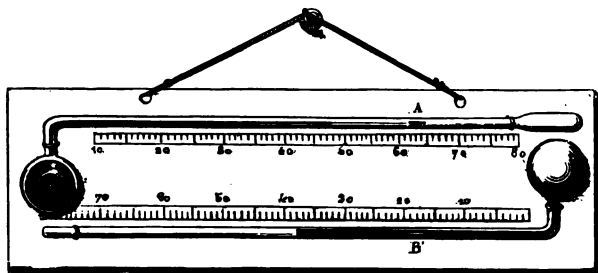


Fig. 6.

limits of these variations within a given time. Thus, heat being apparently the most effective agent in producing meteorological phenomena, the determination of the highest temperature of the day, and the lowest during the night, is a prime essential for forming an estimate of the climate of any place. To observe these extremes by means of the ordinary thermometer would be impracticable, from the constant watchfulness which would be necessary. Hence the utility and importance of 'self-recording' thermometers are evident. A thermometer constructed to register the highest temperature is usually called a *maximum thermometer*; one to show the lowest temperature is termed a *minimum thermometer*; and if made to record both

extremes of temperature it is designated a *maximum and minimum thermometer*.

The instruments described in the succeeding Articles are those most in use.

31. **Rutherford's self-recording thermometers.**—Dr. John Rutherford invented a maximum and also a minimum thermometer, and his arrangement for obtaining a complete instrument for the registration of both extremes consisted simply in mounting a maximum thermometer and a minimum thermometer upon the same frame or slab, as shown in *fig. 6*. The one, *A*, contains mercury; the second, *B*, alcohol. In the tube of the former is a small piece of iron wire which moves in it freely, being pushed along by the mercury as it expands. When the tube is placed in the vertical position, with the mercurial bulb downwards, the iron wire falls upon the mercury; and when in the horizontal position, being pushed to the right by the expansion of the mercury, it will remain at the most extreme point to which the mercury may have moved it, and will not follow the mercury in its contraction. It will thus remain as an indication of the highest temperature to which the instrument has been exposed.

The tube of the alcohol thermometer contains, in like manner, a small piece of coloured glass, having a knob at each end; this allows the alcohol to pass it freely from right to left. But when the alcohol contracts, and moves towards the bulb, it carries with it the glass index *B*, which, consequently, remains in whatever position is given to it when the thermometer has been exposed to the lowest temperature. Thus, while *A* shows the *maximum*, *B* shows the *minimum* temperature to which the instrument has been exposed.

32. **Megretti and Zambra's maximum thermometer.**—This is shown in *fig. 7*, and consists of a glass tube containing mercury fitted on an engraved scale. The part of the thermometer tube above the mercury is entirely free from air; and at point *A*, in the bend above the bulb, is inserted and fixed



Fig. 7.

with the blow-pipe a small piece of solid glass or enamel which acts as a valve, allowing mercury to pass on one side of it when heat is applied, but not allowing it to return when the thermometer cools. When mercury has been once made to pass the contraction, which nothing but the expansion caused by heat can effect, and has risen in the tube, the upper end of the column

registers the maximum temperature, because on a decrease of heat the contraction of mercury takes place *below the bend* in the tube, leaving the whole column of mercury in the tube till the instrument is disturbed. To return the mercury to the bulb it must be removed from its support, held perpendicularly with the bulb downward, and slightly shaken.

The chief recommendation of this thermometer is its simplicity of construction, enabling it to be used with confidence and safety. In many respects it may be said to be the best which has yet been constructed for maximum temperature.

33. **Walferdin's maximum thermometer.**—This instrument is represented in *fig. 8*. It consists of a tube at the top of which is a small reservoir to receive the mercury, which overflows by expansion. When it is required to prepare the instrument for use, it is inverted, so that the extremity of the tube will be immersed in the mercury contained in the upper reservoir then turned downwards. The instrument in this inverted position, is exposed to a temperature lower than any to which it will be subject in the observations about to be made. The instrument is then restored to its proper position, when the tube will be full to the top. As the temperature to which it is exposed rises, the mercury, by its expansion, is forced out of the tube, and discharged from its point into the upper reservoir; and this discharge continues until the temperature reaches its maximum height, after which the mercury contracts, and the column falls in the tube.



Fig. 8. To determine the highest temperature to which the instrument has been exposed, it will be only necessary to compare it with another thermometer, immersing both in the same bath, until the column rises to the summit of the tube. The temperature then indicated by the standard thermometer will be that to which the thermometer has been exposed.

Walferdin has also constructed thermometers to register

the minimum temperature, but they are not so convenient as the others described in this chapter.

34. Baudin's alcohol minimum thermometer.—This instrument resembles Rutherford's thermometer in appearance: its indications are given by the expansion and contraction of alcohol, and its minimum temperature is likewise registered by a glass index being pulled back and left behind by the alcohol, as in Rutherford's instrument. There is, however, a great improvement in Baudin's instrument; for whilst Rutherford's thermometer can only register in a horizontal position, Baudin's can be used either horizontally or vertically, as necessity may require. This important change is effected in the following manner:—Instead of the index in the thermometer being loose and free to run up and down according to the position in which the instrument is held, as in Rutherford's, the index in the new instrument is made to fit the bore of the tube as nearly tight as possible, so much so that in holding the thermometer even upside down, or shaking it, the index will not shift from its position. In order to set the index, there is introduced behind it a piece of solid glass, about one-and-a-half inch in length, which moves freely in the alcohol. The addition of the weight of this piece of glass on the top of the index, when turned upside down, forces the index down to the edge of the alcohol, where it is left, as in the case of the ordinary Rutherford's thermometer. The instrument is then ready for observation, and may now be hung up either horizontally or vertically. The index, although immovable *per se*, is by the alcohol drawn back, as in the ordinary minimum, and its indications are read off on the scale from the top of the index.

35. Negretti and Zambra's mercurial minimum thermometers.—These celebrated makers have constructed two forms of this instrument. The one represented in *fig. 9* has a cylindrical bulb of large size, in order to allow the internal diameter of the tube to be greater than that generally used for thermometrical purposes, so that a steel index, pointed at both ends, may move freely within when required. *In use* the thermometer is suspended perpendicularly with the steel index resting on the surface of the mercurial column. As the mercury in the cylinder contracts from the effect of cold, that in the tube descends, and the index by its own weight follows it. When the mercury expands and rises in the tube, it presses the index on one side, and exerting a lateral pressure on the needle, it jams it to one side of the tube, where it remains firmly fixed, leaving the upper point of the needle indicating

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the minimum temperature. To extricate the needle from the mercury a magnet is used.

The other form is represented in *fig. 10*. In the supplementary tube *B* there is a small plug of platinum wire inserted. When the



Fig. 9.

thermometer is inclined, the mercury flows from the end of the tube *B* until it reaches the plug *C*; there it stops in consequence of the adhesion of the mercury to the platinum, and it then indicates the present temperature. On a decrease of temperature the mercury recedes in the long or indicating tube *A*, but on an increase it rises in the short tube *B*, leaving the long column of mercury indicating the minimum temperature. In *fig. 11* the essential portion of the instrument is shown enlarged.

36. Casella's mercurial minimum thermometer.—

The general form and arrangement of this instrument is shown in *fig. 12*. A bent tube with large bore, *a*, has at the end a kind of diaphragm of glass, formed by the abrupt junction of a small chamber, *c*, the inlet to which at *b* is larger than the bore of the indicating tube; a narrow channel, not shown in the figure, connects

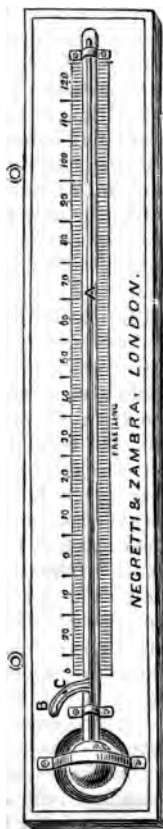


Fig. 10.

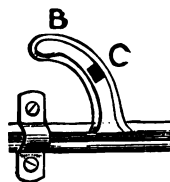


Fig. 11.

finding an easier passage into the small pear-shaped chamber attached.

To set the instrument, it is placed in a horizontal position, with the back plate, *d*, suspended on a nail, and the lower part resting on a hook, *c*. The bulb end may now be gently raised or lowered, causing the mercury to flow slowly until the bent part, *a*, is *full* and the chamber, *b c*, *quite empty*. At this point the flow of mercury in the long stem of the tube is arrested, and the column indicates the exact temperature of the bulb, or the air, at the time. On an increase of temperature the mercury will expand into the small chamber, *b c*; and a return of cold will cause its recession from this chamber only, until it reaches the diaphragm, *b*. Any further diminution of heat withdraws the mercury down the bore to whatever degree the diminution of temperature may attain; there it remains until further withdrawn, or till reset for future observation.

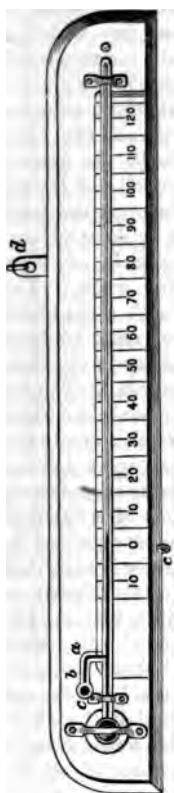


Fig. 12.

37. Size's self-registering thermometer.—This instrument, which is shown in *fig. 13*, consists of a long cylindrical bulb, united to a tube of more than twice its length, bent round each side of it in the form of a syphon, and terminated in a smaller, oval-shaped bulb. The lower portion of the syphon is filled with mercury; the long bulb, the other parts of the tube, and part of

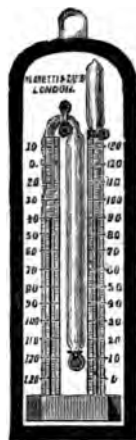


Fig. 13.

the small bulb, with highly rectified alcohol. A steel index moves in the spirit in each limb of the syphon. The two indices are terminated at top and bottom with a bead of glass to enable them to move with the least possible friction, and without causing separation of the spirit, or allowing mercury to pass easily. They would, from their weight, always rest upon the mercury; but each has a fine hair tied to its upper ex-

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tremity and bent against the interior of the tube, which acts as a spring with sufficient elasticity to keep the index supported in the spirit in opposition to gravity.

The instrument acts as follows:—A rise of temperature causes the spirit in the long tube to expand, and press some of the mercury into the other limb of the syphon, into which it rises also from its own expansion, and carries the index with it until the greatest temperature is attained. The lower end of this index then indicates upon the engraved scale the maximum temperature. As the temperature falls the spirit and the mercury contract, and in returning towards the bulb the second index is met and carried up by the mercury until the lowest temperature occurs, when it is left to indicate upon the scale the minimum temperature. The limb of the syphon adjoining the bulb requires, therefore, a descending scale of thermometric degrees; the other limb an ascending scale. The graduations must be obtained by comparisons with a standard thermometer under artificial temperatures, which must be done very carefully, in order to correct for the inequality in the bore of the tube, and the irregular expansion of the alcohol. The instrument is set for observation by bringing the indices into contact with the mercury by means of a small magnet, which attracts the steel through the glass, so that it is readily drawn up or down.

38. **Photographic mode of registering temperatures.**—A much more complete register of the indications of a thermometer, at every instant during any period of time, is obtained by means of photography. A sheet of sensitized paper is mounted on a vertical cylinder just behind the mercurial column in the thermometer. The thermometer is also in a vertical position, and is surrounded by a cover of blackened zinc, with the exception of a narrow vertical slit just behind the mercurial column. A strong beam of light from a lamp or gas flame is concentrated by a cylindrical lens, and if the thermometer were completely empty of mercury this beam of light would pass through the slit in the cover and the bore of the instrument without hindrance, and a bright vertical line would thus be thrown on the paper. But as the beam of light is intercepted by the mercury in the tube, which for this purpose is made broad and flat, only the portion of the paper above the top of the mercurial column receives the light, and is photographically affected. The cylinder is made to revolve slowly by clockwork, and if the mercury stood always at the same height the boundary between the blackened and the reflected parts of the paper would be straight and horizontal, in consequence of

the horizontal motion of the paper itself. In reality, the rising and falling of the mercury, combined with the horizontal motion of the paper, causes the line of separation to be curved or wavy, and the height of the curve above a certain line of reference is a measure of the temperature at each instant during the time of revolution of the cylinder. The apparatus is usually called a *thermograph*.

39. Alcohol thermometers.—Since mercury freezes at -39° , it cannot be used at temperatures which are below its freezing point. Thermometers which are to be used for measuring very low temperatures are, therefore, filled with alcohol, no degree of cold yet observed in nature or attained by artificial processes having frozen it. The alcohol is usually coloured, so as to render the column easily observable in the tube. The alcohol thermometer cannot be used for temperatures above 60° or 65° , for its expansion, like that of other liquids, is very irregular in proportion as the boiling point is approached, which for pure alcohol is about 78° . The alcohol thermometer is usually graduated by comparing it with a mercurial thermometer, both thermometers being simultaneously placed in the same conditions with reference to temperature.

40. Air thermometers.—Atmospheric air is an excellent thermometric fluid. It has the advantage over liquids in retaining its gaseous state at all temperatures, and in the perfect uniformity of its dilatation and contraction.

It is also highly sensitive, indicating changes of temperature with great promptitude. Since, however, it is not visible, its expansion and contraction must be rendered observable by expedients which interfere with and render complicated its indications.

The air thermometer of Drebbel, or, according to some, of Sanctorius, is represented in *fig. 14*.

A glass tube, *A B*, open at one end, and having a large thin bulb *C* at the other, is placed with its open end in a coloured liquid, so that the air contained in the tube shall have a less pressure than the atmosphere. A column of the liquid will therefore be sustained in the tube *A B*, the weight of which will represent the difference between the pressure of the external air and the air enclosed in the tube.

If the bulb *C* be exposed to a varying temperature, the air included in it will expand and contract, and will cause the column of coloured liquid in the tube *A B* to rise and fall, thereby indicating the changes of temperature.



Fig. 14.

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In *fig. 15* another form of the air thermometer is shown. The bulb *c* is half filled with air, and the expansion or contraction of the latter causes the coloured liquid to rise or fall in the tube *A B*. This form of the air thermometer is usually called *Amonton's thermometer*. In recent times more accurate instruments of this class have been constructed, which will be described further on.



Fig. 15. of two glass bulbs, *A* and *B*, connected by a rectangular glass tube. In the lower part of the tube a small quantity of dilute sulphuric acid coloured with litmus is placed :

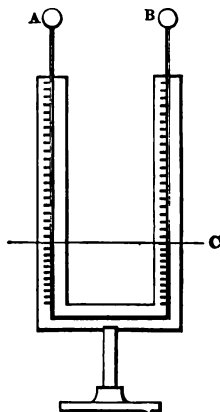


Fig. 16.

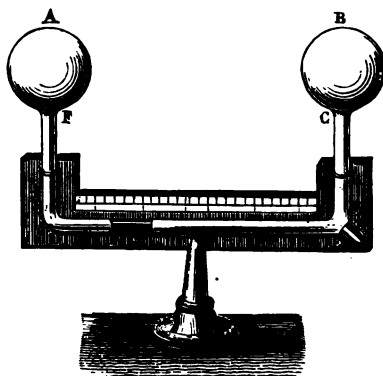


Fig. 17.

it is of importance to use a liquid which does not give off vapours at ordinary temperatures, and dilute sulphuric acid fulfils this condition very satisfactorily. Atmospheric air is contained in the bulbs and tube, separated into two parts by the liquid. The instrument is so adjusted that when the liquid rises to the same level, *c*, on both sides, the air in the bulbs has the same pressure ; and, having equal volumes, the quantities at each side of the liquid are necessarily equal. If the bulbs be affected by different temperatures, the liquid will be pressed *from that side at which the temperature is greatest, and the*

extent of its departure from the zero or level is indicated by the scale.

The form of differential thermometer represented in *fig. 17* is sometimes called *Rumford's thermoscope*. It has larger bulbs than *Leslie's thermometer*, and the index, *g*, consists of a single drop of liquid. If the bulbs are both of the same temperature, and the index is in the middle, the zero is at each end of the horizontal leg, and the rest of the graduation rests on the same principle as in *Leslie's thermometer*, that is, one of the bulbs being raised to a temperature higher than the other, the difference is marked along the scale, both above and below zero, and divided into equal parts. The appendix *z* is intended to regulate the apparatus; when there is too much air in one of the bulbs, the index is passed into the appendix, so that air can reach the other bulb. By inclining the thermoscope, the index passes out, and can be brought to occupy its proper position after a few trials.

Its extreme sensitiveness, in virtue of which it indicates changes of temperature too minute to be observed by common thermometers, renders it extremely valuable as an instrument of scientific research.

By this instrument, changes of temperature not exceeding the 6,000th part of a degree are rendered sensible.

42. *Breguet's metallic thermometer*.—This instrument, founded upon the unequal dilatation of different metals, is represented in *fig. 18*. Three very thin strips, of platinum, gold, and silver, being soldered face to face, are formed into a spiral or helix. Having fixed the upper extremity of this to a support, a light needle is attached at right angles to the helix at the lower end. According as the metal of the helix expands and contracts, the lower extremity to which the needle is attached will move round a spiral, and the needle will consequently revolve like the hand of a watch. A graduated circle, like the dial of a watch, is placed under it to indicate its motions. The silver, which is the most dilatible of the three metals, forms the inner face of the helix, and the platinum, which is the least dilatible, the outer; the gold being included



Fig. 18.

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between them. When the temperature rises, the silver being more dilated than the platinum or gold, the helix unrolls itself; and when the temperature falls, the contrary effect takes place. The needle, therefore, in the two cases is turned in contrary directions. The gold is placed between the two other metals because, having an intermediate dilatability, it moderates their mutual effect. If two metals only were employed, the difference of the dilatations might produce a rupture.

This thermometer is graduated by comparing it with a standard thermometer.

43. Pyrometers.—The range of the mercurial thermometer being limited by the boiling point of mercury, higher temperatures are measured by the expansion of solids, whose points of fusion are at a very elevated part of the thermometric scale. The solids which are best adapted for this purpose are the metals. Being good conductors, these are promptly affected by heat, and their indications are immediate, constant, and regular.

Instruments adapted for the indication and measurement of this high range of temperature are called *pyrometers*.

To graduate a pyrometer, let the metallic bar be immersed successively in melting ice and boiling water, and let its length at these temperatures be accurately measured. Their difference being divided by 100, the quotient will be the increment of length corresponding to one degree of temperature; and this increment being multiplied, the length corresponding to any proposed temperature may be ascertained.

Let L° express the length of the bar at the temperature 0° .

Let L' express its length at the temperature 100° .

Let i express the increase of length corresponding to 1° .

We shall then have

$$i = \frac{L' - L^{\circ}}{100}.$$

If L express in general the length of the bar at the temperature expressed by T , we shall have

$$L = L^{\circ} + i \times T$$

which means nothing more than that the length at the temperature T is found by adding to the length at the temperature 0° as many times the increment corresponding to 1° as there are degrees in T above 0° .

The instrument represented in *fig. 19* is one of the most simple forms of pyrometer.

A rod of metal, H , is in contact at one end with the point of a screw, g , and at the other with a lever, A , near its fulcrum.

This lever is connected with another so as to form a compound system, such that any motion imparted by the rod to the point on the lever A in contact with it is augmented in a high ratio. A lamp placed under the rod H raises its temperature; and as it is resisted by the point of the screw g, its dilatation must take effect against the lever A, which, acting on the second lever D, will move the index on the graduated arc A B. The ratio of this motion to that of the end of the bar acting on the lever being known, the quantity of dilatation may be calculated. Thus let us suppose that the lever D have a length of l_2 inches, and is, for the sake of simplicity, moved only by one small lever of length l_1 , against which the heated bar is pressing. Further, let the angle through which the lever D moves while the bar,

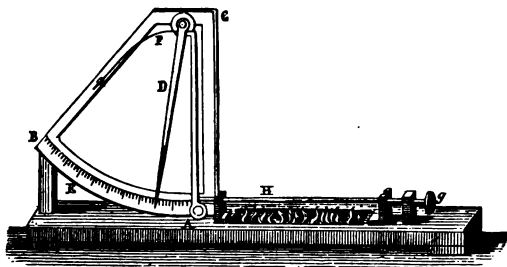


Fig. 19.

originally of length L , is heated from t degrees to t_1 equal L_1 degrees of temperature, be w , and the length of the expanded bar at the temperature t equal L_1 . Then by geometry, we have :

$$\text{Length of arc through which D has moved} = \frac{l_2 \pi w}{180},$$

$$\text{but} \quad L_1 - L : \frac{l_2 \pi w}{180} :: l_1 : l_2 \text{ (approximately),}$$

$$\text{or} \quad L_1 - L = \frac{l_1 \pi w}{180}$$

and therefore the expansion for 1°

$$= \frac{L_1 - L}{t_1 - t} = \frac{l_1 \pi w}{(t_1 - t) 180}.$$

44. **Wedgewood's Pyrometer.**—It is found that the paste formed by saturating potter's earth with water, when exposed to high temperatures, instead of being dilated, like other solid bodies, is contracted. This apparent exception to the general

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thermal law is explained by the fact that the increase of temperature evaporates a part of the water which has given plasticity to the clay, and that the particles of the clay are then brought closer together by their natural cohesion. Whatever be the cause by which this effect is explained, the degree of contraction produced has been considered sufficiently regular to be taken as a measure of the temperature to which the paste has been exposed, and upon this principle Wedgwood's pyrometer is based.

Three bars of copper, each 6 inches long, are fixed upon a plate of metal in juxtaposition, as shown in *fig. 20*, but not exactly parallel. The edges of the first and second bar at one end are exactly $\frac{1}{2}$ an inch asunder, while at the other end the

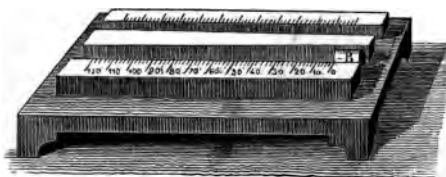


Fig. 20.

distance between them is less than $\frac{1}{2}$ an inch by 1 line, or the 12th of an inch. In like manner, the edges of the second and third bars are separated by a space less than $\frac{1}{2}$ an inch by 1 line at one end, and by a space less than $\frac{1}{2}$ an inch by 2 lines at the other end.

A number of small cylinders of potter's earth, exactly $\frac{1}{2}$ an inch in diameter, baked in an oven at the temperature of 100° are provided. These will, therefore, exactly correspond with the interval between the bars of the pyrometer at their widest end. When it is desired to ascertain, for example, the temperature of a furnace, one of these cylinders is placed in it, and after its temperature has been elevated to that of the furnace, it is withdrawn and allowed to cool; it is then inserted at the widest end of the bars, between which it will now enter in consequence of its contraction. It is advanced between them as far as it will go, as shown in the figure. The bars being graduated, the distance through which it advances shows the extent of its contraction, and this extent is taken as the measure of the temperature which has produced it.

These instruments, however, give results which are attended with several causes of uncertainty, the principal of which is, that

the extent of the contraction depends not only on the temperature to which the cylinder has been exposed, but to the length of time during which it has been subject to that temperature.

45. **Brogniart's pyrometer.**—M. Brogniart, while director of the Porcelain Manufactory at Sèvres, constructed a pyrometer similar in principle to that shown at *fig. 19*, consisting of a bar of steel, silver, or platinum, placed within the oven, one end being fixed, and the other acting upon a rod of porcelain which projects from the extremity of the furnace in which the apparatus is placed. This rod presses against the smaller arms of a bent lever, the longer arm of which moves along a graduated arc. In proportion as the metallic bar in the furnace elongates by increase of temperature, it presses the porcelain rod and moves the lever, and the expansion may then be easily derived in the manner shown in Art. 43.

46. **Borda's pyrometric standard measure.**—The standards used as measures of length for ascertaining distances where great accuracy is required, such as in measuring the bases in geographical surveys, are usually rods of metal. But since these are subject to a change of length with every change of

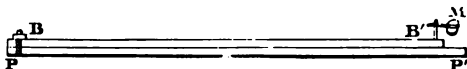


Fig. 21.

temperature, it would follow that the results of any measurement made by them would be attended with corresponding errors.

For the common purposes of domestic and commercial economy, such errors are too trifling to be worth the trouble of correcting; but this is not the case when they are applied to scientific purposes. It is necessary in such cases to observe the temperature of the rods at the moment each measurement is made.

In the operation by which the great arc of the meridian in France was measured, a very beautiful expedient was contrived by Borda, in which the bar itself is converted into a thermometer which indicates its own temperature. This expedient was again rendered available for the series of experiments made by Dulong and Petit, to ascertain the dilatation of bodies by heat.

A bar of platinum, $P P'$, *fig. 21*, was connected at one extremity with a similar bar of brass $B B'$, of very nearly equal length.

The two bars, being screwed or riveted together at the extre-

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mity B, were free at every other point. Near the extremity P' of the bar of platinum, and immediately under the extremity B' of the brass bar, a very exact scale was engraved, the divisions of which marked the millionth part of the entire length of the rod. The extremity B' of the brass bar carried an index, which moved upon the divided scale. Over the point of this was placed a microscope M, by which its position could be ascertained, and by which the divisions of the scale could be more exactly read off.

If the two bars, P P' and B B', were equally dilatable, it is evident that the same change of temperature affecting both would make no change in the position of the index ; but, brass being more dilatable than platinum, the index pushed by the expansion of the bar B B' would be moved towards P' through a space greater than that by which the bar P P' would be lengthened, and, consequently it would be advanced upon the scale through a space equal to the difference between the dilatation of the two bars.

The manner of graduating the scale upon P P' was as follows. The compound bar being submerged in a bath of melting ice, the position of the index was observed. It was then transferred to a bath of boiling water, when the position of the index was again observed.

The interval between these two positions being divided into 100 equal parts, each part would represent one degree of temperature ; or, if such division were too minute to be practicable, it might be divided into a less number of equal parts, as, for example, 20, in which case each division would correspond to 5°. When the index, as most frequently happens, stands between two divisions of the scale, it is necessary to estimate or measure its distance from one of these divisions, in order to express its exact position. This is accomplished by the contrivance called a *vernier*, which has been already described in its application to barometers (see 'HYDROSTATICS,' page 138).



Fig. 22.

47. **The weight thermometer.**—This is a kind of pyrometer which differs from a mercurial thermometer in having no scale attached, the temperature to be ascertained being found by calculation. It consists, as shown in *fig. 22*, of a cylindrical glass reservoir, closed at one end, and terminated at the other by a short capillary glass tube, which is so bent that

when the thermometer is placed in the position in which it is to be used its open end points vertically downwards. The mode of using it is as follows : The thermometer is weighed while empty, and the reservoir and tube are then completely filled with pure mercury, the whole of the air being carefully expelled by boiling, and allowing the instrument to cool while the open end of the capillary tube dips under the surface of the mercury, as in the usual process of filling a barometer or thermometer. By surrounding the thermometer with melting ice, the instrument itself, as well as the mercury contained in it, is brought to the temperature of 0° . When this temperature is reached by every part of it, the vessel of mercury is removed from under the open end of the capillary tube and is replaced by a small weighed capsule. The ice is now removed, and the outside of the thermometer carefully dried. As the mercury contained in it returns to the temperature of the air (supposed above 0°), it expands, and, consequently, some of it escapes by the capillary tube into the weighed capsule. The thermometer, and the capsule containing the mercury which has escaped from it, are now placed together in the balance and weighed ; by deducting from the gross weight so obtained the weight of the instrument when empty, and that of the capsule, we obtain the weight, w , of the quantity of mercury which fills the thermometer at 0° .

The instrument is next heated to 100° , by immersing it in the steam of boiling water, the same precautions being taken as in fixing the boiling point of the ordinary graduated thermometer, and the mercury which escapes is collected in the weighed capsule and weighed. Let w be the weight of the whole quantity of mercury which escapes from the thermometer when it is heated from 0° to 100° ; thus the coefficient of apparent expansion (see further on, Chapter IV.) of the mercury contained in the thermometer will be

$$\delta = \frac{w}{(w - w)100} \quad \text{. . . (I).}$$

Similarly, if w_t be the weight of mercury which escapes from the thermometer when it is heated to any other temperature, t° , which it is required to determine, we have

$$\delta = \frac{w_t}{(w - w_t)t} \quad \text{. . . (II).}$$

Hence we get

$$\frac{w}{(w - w)100} = \frac{w_t}{(w - w_t)t}$$

or

$$t = \frac{w - w}{w - w_t} \times \frac{w_t}{w} \times 100$$

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The value of δ , deducible from equation (I) was found by Dulong and Petit (who were the first to employ the weight thermometer) to be equal to $\frac{1}{8480}$, and by substituting this value in equation (II) the value of t is given independently of the preliminary experiment above described, in which the thermometer is heated to 100° .

A few more recent forms of pyrometers will be described further on.

CHAPTER III.

THE EXPANSION OF SOLIDS.

48. Expansion in three dimensions.—Of all the states of aggregation of matter, that in which it is least susceptible of dilatation is the solid state. This may be explained by the energy of the cohesion of the component particles of the body, which is the characteristic property of the solid state. It is the nature of heat, by whatever hypothesis that agency can be explained, to introduce a repulsive force among the molecules of the body it pervades. In solid bodies this repulsive force, acting against the cohesive force, diminishes the tenacity of the body. The component parts have a tendency to separate from each other, and hence arises the phenomenon of dilatation; but so long as the body preserves the character of solidity, the separation of the component molecules cannot exceed the limits of the play of cohesion; and as these limits are very small, no dilatation which is consistent with the character of a solid can be considerable.

If a solid body be perfectly homogeneous, it will dilate uniformly throughout its entire volume for an uniform elevation of temperature. Thus, the length, breadth, and depth will, in general, be all augmented in the same proportion.

It is a principle of geometry, that when a solid body, without undergoing any change of figure, receives a small increase of magnitude, its increase of surface will be twice, and its increase of volume thrice, the increase of its linear dimensions. That is to say, if its length be augmented by a thousandth part of its primitive length, its surface will be augmented by *two* thousandth parts of its primitive surface, and its volume by *three* thousandth parts of its primitive volume. This is not true in a strictly mathematical sense, but it is sufficiently near the truth for all practical purposes.

Thus, let us take a square surface, of which each side measures exactly one foot. The area of this surface will be one square foot. Suppose now that each side expands by heat, and that it measures $1 + a$ feet, a being the addition to its previous length. The area will now evidently be

$$(1 + a)(1 + a) = 1 + 2a + a^2.$$

Similarly, if we take the volume of a cube, then under precisely the same suppositions as regards the magnitude of each edge as in the case of the side of the square, we shall find its volume after expansion to be

$$(1 + a)(1 + a)(1 + a) = 1 + 3a + 3a^2 + a^3.$$

Now in each of these cases a is a very small quantity, and the square or cube is still less than this quantity. Neglecting therefore those terms which contain a^2 and a^3 , we come to the following general principle: Since all solid bodies of uniform structure, when heated or cooled, expand or contract, without change of figure, and since, while the change of their linear dimensions can be easily and exactly ascertained, that of their surface or volume can only be determined with considerable difficulty: the changes of these last are deduced from the first by multiplying the increment of linear expansion by 2 for the increment of surface, and by 3 for the increment of volume.

49. **Measure of the force of dilatation.**—The force with which solid bodies dilate and contract is equal to that which would compress them through a space equal to their dilatation, and to that which would stretch them through a space equal to the amount of their contraction. Thus, if a pillar of metal one hundred inches in height, being raised in temperature, is augmented in height by a quarter of an inch, the force with which such increase of height is produced is equal to a weight which being placed upon the top of the pillar would compress it so as to diminish its height by a quarter of an inch.

In the same manner, if a rod of metal one hundred inches in length be contracted by diminished temperature so as to render its length a quarter of an inch less, the force with which this contraction takes place is equal to that which being applied to stretch it would cause its length to be increased by a quarter of an inch.

This principle is often practically applied in cases where great mechanical force is required to be exerted through small spaces. Thus, in cases where the walls of a building have been thrown out of the perpendicular, either by the unequal subsidence of the foundation or by the incumbent pressure of the roof, they

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have been restored to the perpendicular by the following arrangement :—

A series of iron rods are carried across the building, passing through holes in the walls, and are secured by nuts on the outside. The alternate bars are then heated by lamps until they expand, when the nuts, which are thus removed to some distance from the walls by the increased length of the bars, are screwed up so as to be in close contact with them. The lamps are then withdrawn, and the bars allowed to cool. In cooling they gradually contract, and the walls are drawn together by the nuts through a space equal to their contraction. Meanwhile, the intermediate bars have been heated and expanded, and the nuts screwed up as before. The lamps being again withdrawn and transferred to the first set of bars, the second set are contracted in cooling, and the walls are further drawn together. This process is continually repeated, until at length the walls are restored to their perpendicular position.

In all cases where moulds are constructed for casting objects in metal, the moulds must be made larger than the intended magnitude of the object, in order to allow for its contraction in cooling. Thus the moulds for casting cannon balls must always be greater than the calibre of the gun, since the magnitude of the mould will be that of the ball when the metal is incandescent, and therefore greater than when it is cold.

Hoops surrounding water-vats, tubs, and barrels, and other vessels composed of staves, and the tires surrounding wheels, are put on in close contact at a high temperature, and, cooling, they contract and bind together the staves or fellies with greater force than could be conveniently applied by any mechanical means.

50. Compensators.—In all structures composed of metal, or in which metal is used in combination with other materials, such as roofs, conservatories, bridges, railings, pipes for the conveyance of gas or water, rafters for flooring, &c., compensating expedients must be introduced, to allow the free play of the metallic bars in dilating and contracting with the vicissitudes of temperature to which they are exposed during the change of seasons.

These expedients vary with the way in which the metal is applied, and with the character of the structure. Pipes are generally so joined from place to place as to be capable of sliding one within another, by a telescopic joint. The successive rails which compose a line of railways cannot be placed end to end, but space must be left between their extremities for dilatation.

Sheet lead and zinc, both of which metals are very dilatable, when used to cover roofs, where they are especially exposed to

vicissitudes of temperature, are liable to blister in hot weather by expansion and to crack in cold weather by contraction, unless expedients are adopted to obviate this: zinc, being much more dilatable than lead, is more liable to these objections.

When ornamental furniture is inlaid with metal without providing for its expansion, the metal, being more dilatable than the wood, is liable, in a small room, to expand and start from its seat.

Various other applications of these principles will be described in future articles.

51. Coefficient of expansion.—It is found that solid bodies in general suffer a nearly uniform rate of dilatation through a range of temperature extending from the zero-point of the thermometer to 100 degrees; that is to say, the increments of length, to speak only of one dimension, which attend each degree of temperature which the body receives are equal. If, therefore, the entire increment of length which such a body undergoes when it is heated from 0° to 100° be divided by 100, the quotient will be the increment of length which it receives when its temperature is raised one degree. If we suppose that the body under consideration had at 0° the unit length, that is a length of one foot, or one yard, for example, then the quotient thus obtained will give us the increment of the unit length when the particular substance is heated from 0° to 1° ; this quantity is called the *coefficient of linear dilatation* of the particular substance.

Similarly, the *coefficient of cubical dilatation* is the increase of the unit volume of a substance, say a cubic yard, or a cubic foot, when it is heated from 0° to 1° .

When solids are elevated to temperatures much above 100° , and more especially when they approach those temperatures at which they would be fixed or liquefied, the dilatations are not uniform. As the temperature is raised, the rate of dilatation is increased; that is to say, a greater increment of volume attends each degree of temperature.

52. Experimental determination of the coefficients of expansion of solids.—Many elaborate and ingenious methods have been applied by physicists to the determination of coefficients of linear and cubical expansion of bodies. One of the first methods applied for the purpose was that adopted by *Lavoisier* and *Laplace*. The bar AB , *fig. 23*, whose expansion is to be determined, has one end fixed at A , while the other can move freely, pushing before it the lever OB , which is movable about the point O and carries a telescope whose line of sight is directed to a scale at some distance. It is evident that a displacement $B B'$ will correspond to a considerably greater length, OO' , on the scale, which will increase with the distance of the

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scale from the telescope. The ratio of CO' to BB' is equal to the ratio of OC to OB , and is the same throughout the whole course of experiments. In order to determine this ratio once for all, we have only to measure the distance CO' on the scale corresponding to a *known* displacement, BB' . In the actual experiments the bar of which the expansion is to be measured is placed horizontally in a trough, which rests between four massive uprights of hewn stone. One of the extremities of the bar rests at A against a fixed perpendicular bar firmly joined to two of the uprights, while the other extremity pushes the bar B so as to produce the rotation of an horizontal axis, which carries

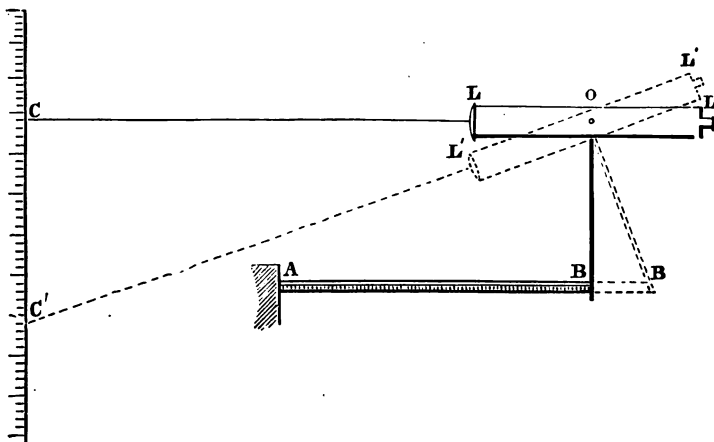


Fig. 23.

with it in its rotation the telescope LL , which is directed to the scale. The first step is to surround the bar with melting ice and then observe the number on the scale marked by the line of sight of the telescope. The temperature of the trough is then raised and the corresponding increase of length is measured.

Laplace and Lavoisier discovered by these experiments that the expansion of solids is sensibly uniform between 0° and 100° ; above this latter point it increases as the temperature rises.

53. Roy and Ramsden's method.—A simpler and direct method of measuring expansions was employed by Roy and Ramsden. The apparatus consists of three troughs, A , B , C , in *fig. 24*, of which the first and last contains iron bars, while the *middle one* contains the bar of which the dilatation is to be *measured*. To the two extremities of the iron bar contained in

the first trough, the eye-pieces of two microscopes are fixed, the object glasses being attached to the corresponding extremities of the bar in the middle trough. These microscopes are directed towards two marks attached to the extremities of the iron bar in the further trough, c. The first and third troughs are kept filled with melting ice, so that the iron bars in these are always

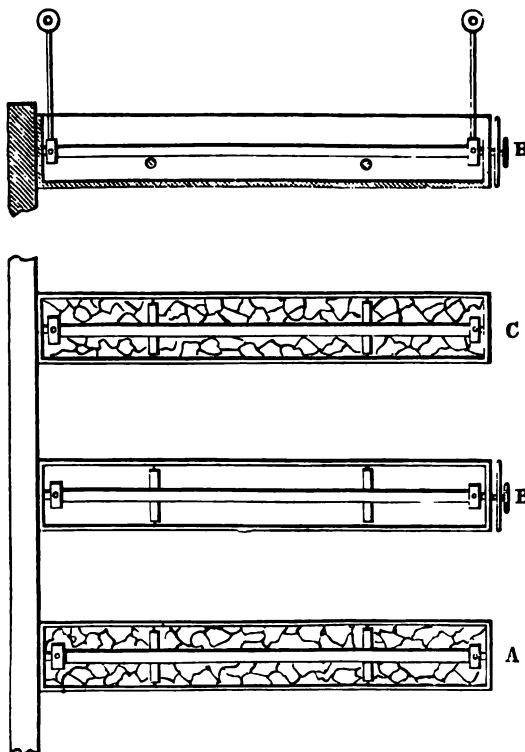


Fig. 24.

of the same temperature. These bars are permanently fixed at one end and movable through a collar at the other. The points of attachment of the eye-pieces of the two microscopes to the first bar may thus be regarded as rigidly fixed; likewise the points of attachment of the two marks which are fastened to the extremities of the iron bar in the third trough, inasmuch as there is no expansion or contraction of these two bars through

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change of temperature. On the other hand, the bar in the middle trough is first of all placed in ice and afterwards in water which is heated by lamps in order that the dilatation of this bar may be measured. This middle bar rests upon rollers, as shown at B at the top of the figure, which is a vertical section through the length of the middle trough, and by means of a screw on the left hand (not shown in the figure) the left-hand end of the bar is always kept in the same position. At 0° the eye-pieces, object glasses and marks are so adjusted in position that the optical axis of the two former is in a line with the centre of the marks; this adjustment is made by means of wire crosses in the eye-pieces. Now, when expansion takes place, the right-hand extremity of the middle bar, and consequently the object glass attached to it, moves towards the right, and the middle of the wire cross will no longer coincide with the mark. It may, however, be brought back to the original position and coincidence may be restored by means of a micrometer screw on the right end, which moves the cross and allows of measuring the number of turns and fractional parts of a turn through which it was displaced in consequence of the expansion of the bar.

54. **Table of Expansions.**—In the following table are given the rates of linear dilatation of solid bodies as determined by these and other observers.

LINEAR EXPANSION OF SOLIDS BY HEAT.

Dimensions which a bar takes at a 100° whose length at 0° is 1'000000.

Substance	Observer		Expansion
Glass tube	Smeaton	1'00083333	
"	Roy	1'00077615	
"	Deluc's mean	1'00082800	$\frac{1}{1178}$
"	Dulong and Petit	1'00086130	$\frac{1}{1178}$
"	Lavoisier and Laplace	1'00081166	$\frac{1}{1178}$
Plate glass	"	1'000890800	$\frac{1}{1178}$
" crown glass	"	1'00087572	$\frac{1}{1178}$
"	"	1'00089760	$\frac{1}{1178}$
"	"	1'00091751	$\frac{1}{1178}$
" rod	Roy	1'00080787	
Deal	Roy	As glass	
Platinum	Borda	1'00085655	$\frac{1}{1178}$
"	Dulong and Petit	1'00088420	$\frac{1}{1178}$
"	Troughton	1'00099180	
" and glass	Berthoud	1'00110000	
Palladium	Wollaston	1'00100000	
Antimony	Smeaton	1'00108300	
Cast-iron prism	Roy	1'00110940	
Cast-iron	Lavoisier, by Dr. Young	1'00111111	
Steel	Troughton	1'00118990	
Steel rod	Roy	1'00114470	
Blistered steel	'Phil. Trans.' 1795, p. 428	1'00112500	
"	Smeaton	1'00115000	
Steel, not tempered	Lavoisier and Laplace	1'00107875	$\frac{1}{1178}$
"	"	1'00107956	$\frac{1}{1178}$

THE EXPANSION OF SOLIDS.

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LINEAR EXPANSION OF SOLIDS BY HEAT—continued.

Dimensions which a bar takes at a 100° whose length at 0° is 1'000000.

Substance	Observer		Expansion
Steel, tempered yellow . . .	Lavoisier and Laplace . .	1'00136900	
" " " at a higher heat	" " " . . .	1'00138600	
Steel	Troughton	1'00123956	1/507
Hard steel	Smeaton	1'00118980	
Annealed steel	Muschenbrock	1'00122500	
Tempered steel	" "	1'00122000	
Iron	Borda	1'00137000	
" " "	Smeaton	1'00115600	
Soft iron, forged	Lavoisier and Laplace . .	1'00125800	
Round iron, wire drawn . .	" "	1'00122045	
Iron wire	Troughton	1'00123504	
Iron	Dulong and Petit	1'00144010	
Bismuth	Smeaton	1'00118203	1/118
Annealed gold	Muschenbrock	1'00139200	
Gold	Ellicot, by comparison . .	1'00146000	
" procured by parting	Lavoisier and Laplace . .	1'00150000	
" Paris standard, unannealed	" "	1'00146606	1/112
" " " annealed	" "	1'00155155	1/111
Copper	Muschenbrock	1'00151361	1/111
" " "	Lavoisier and Laplace . .	1'00191000	
" " "	" "	1'00172244	1/111
" " "	Troughton	1'00171222	1/114
" " "	Dulong and Petit	1'00191880	
Brass	Borda	1'00171821	1/115
" " "	Lavoisier and Laplace . .	1'00178300	
" " "	" "	1'00186671	
Brass scale, supposed from	" "	1'00188971	
Hamburgh	Roy	1'00185540	
Cast brass	Smeaton	1'00187500	
English plate-brass, in rod	Roy	1'00189280	
" " " in a trough	" "	1'00189490	
form	" "	1'00191680	
Brass	Troughton	1'00191680	
" wire	Smeaton	1'00193000	
" " "	Muschenbrock	1'00216000	
Copper 8, tin 1	Smeaton	1'00181700	
Silver	Herbert	1'00189000	
" " "	Ellicot, by comparison . .	1'00210000	
" " "	Muschenbrock	1'00212000	
" of enpel	Lavoisier and Laplace . .	1'00190974	1/111
" Paris standard	" "	1'00190868	1/112
Silver	Troughton	1'00208260	
Brass 16, tin 1	Smeaton	1'00190800	
Speculum metal	" "	1'00193300	
Spelter solder; brass 2, zinc 1	" "	1'00205800	
Malacca tin	Lavoisier and Laplace . .	1'00193765	1/113
Tin from Falmouth	" "	1'00217298	1/113
Fine pewter	Smeaton	1'00228300	
Grain tin	" "	1'00248300	
Tin	Muschenbrock	1'00284000	
Soft solder; lead 2, tin 1	Smeaton	1'00250800	
Zinc 8, tin a little hammered	" "	1'00269200	
Lead	Lavoisier and Laplace . .	1'00284836	1/111
" " "	Smeaton	1'00286700	
Zinc	" "	1'00294200	
Zinc, hammered out 1/2 inch per foot	" "	1'00301100	
Glass, from 0° to 100° . . .	Dulong and Petit	1'00086130	1/101
" from 100° to 200° . . .	" "	1'00091827	1/103
" from 200° to 300° . . .	" "	1'00010114	1/107

The last two measurements by an air-thermometer.

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Messrs. Calvert, Johnson, and Lowe have determined the linear expansion of a considerable number of metals and alloys by a modification of the method above described, for the details of which we must refer to the original paper published in the 'Mechanic's Magazine.'

The following are the linear expansions of simple metals between 0° and 100° C. thus determined:—

Cadmium (pure)	0'00332
Lead (pure)	0'00301
Tin (pure)	0'00273
Aluminium (commercial)	0'00222
Zinc, forged (pure)	0'00220
Silver (pure)	0'00199
Gold (pure)	0'00138
Bismuth (pure)	0'00133
Wrought iron	0'00119
Cast iron	0'00112
Steel (soft)	0'00103
Antimony (pure)	0'00098
Platinum (commercial)	0'00068

55. Influence of physical condition of substance on the rate of expansion.—From the preceding table it will be seen that the coefficients of expansion of the metals vary with their physical condition, being different for the same metal according as it has been cast, hammered and rolled, hardened, or annealed. As a general rule, those operations which increase the density appear also to increase the rate of expansion by heat. But even for substances in apparently the same condition different observers have found very unequal amounts of expansion; this may arise in the case of compound substances, such as glass, brass, or steel, from a want of uniformity in chemical composition, and in simple bodies from slight differences of physical state. Hence, in all cases where great accuracy is required in the determination of the linear expansion, as in rods employed for pendulum observations or for the measurement of the base-lines of surveys, it is impossible to rely upon the results of previous determinations of the expansion of the material in question; but the linear expansion of each individual rod must be determined by a special experiment: this was done, for instance, by De Borda, with each of the four platinum measuring rods (each two toises or twelve French feet long) which were employed in the measurement of the arc of meridian, from which the length of the metre was deduced. As explained in art. 46, brass or copper rods were laid upon the platinum rods, and both were firmly fixed together at one end; the copper rods carried a *divided scale* at the other end, which indicated directly the

twenty-thousandth part of their length, while by means of a vernier attached to the corresponding end of the platinum rods tenths of these divisions, or about the one-hundredth part of a French line, could be read off. In this way, the difference in the expansion of two rods of the same length but different materials can be determined with great accuracy, and if the coefficient of expansion for the material of one rod is known the coefficient of that of the other can be calculated.

If both rods have the same length, L , at 0° , and at t° one has the length $L' = L(1 + at)$, the other the length $L'' = L(1 + a't)$, we have $L' - L'' = Lt(a - a')$, a and a' being the coefficients of expansion of the two metals. But $L' - L''$ is the observed difference of length at the temperature t° ; and hence if a is known a' is easily calculated. In this way Dulong and Petit deduced the linear expansion of copper from that of platinum.

If, on the other hand, the expansion of the material of two rods thus united is known, and can be taken as proportional, within certain limits of temperature, to the indications of the mercurial thermometer, the combination of the two rods may be employed as a metallic thermometer. The measurement of temperatures in this way is specially valuable in the case of standard measures of length, which can thus be made to indicate their own temperature. If, for instance, the two rods have the same length at 0° , and differ at 100° by the amount D , and at t° by the amount d , the temperature is given by the equation $t = \frac{d}{D} 100$.

The unequal expansion of different metals has been taken advantage of for the construction of thermometers of another kind. If two straight strips of different metals are fastened together throughout their whole length, any variation of temperature must cause the compound strip to bend, so that the least expanded metal will be on the concave side, and the most expanded metal on the convex side of the curve. As described in art. 42, Breguet's thermometer is constructed upon the principle just stated, and is made from a compound plate of platinum, gold, and silver, soldered together, the gold in the middle. This is rolled out very thin, and cut into very narrow strips, which are coiled round into spirals. The thermometer consists of such a spiral suspended by one end from a support, and carrying a needle which swings round a divided circle at the other.

Supposing the silver to be inside of the spiral, any rise of temperature will be indicated by the untwisting of the spiral, and a fall of temperature by its twisting more tightly.

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The small mass of this instrument, and the low specific heat of the materials composing it, cause it to indicate changes of temperature very rapidly, and to be affected by very small quantities of heat.

56. **Fizeau's experiments.**—One of the most exact methods of determining linear expansion has been recently designed by M. Fizeau, and applied to the determination of the coefficients of dilatation of a great variety of substances. It rests in prin-

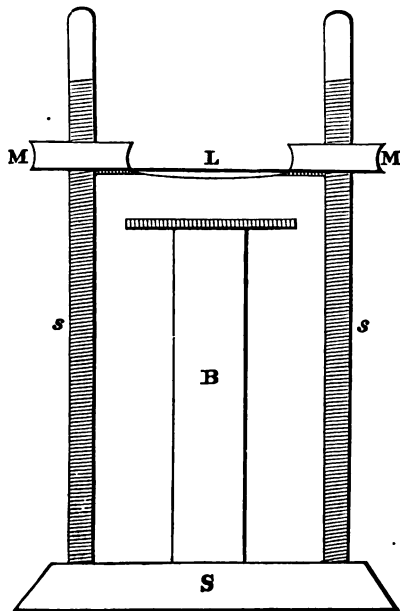


Fig. 25.

ciple on the fact, explained in the volume on 'OPTICS,' that if a convex lens of very long focus be placed in contact with a plane polished surface so that they may be seen in reflected light, phenomena of *interference of light* will be observed : a black spot will appear at the centre, surrounded by a series of concentric rings, alternately light and dark, called Newton's rings. But if the plane surface and lens be separated by even the smallest distance the black spot disappears immediately. In a general manner the method may be employed by means of the following

apparatus. Upon a stand, *s*, *fig.* 25, two upright screws, *ss*, are fixed, with nuts, *mm*, which are furnished with a micrometric arrangement. By means of the nuts the lens *L* can be raised or lowered. The bar *B*, of which the expansion is to be determined, is placed between the screws, and its upper surface is either polished or provided with a thin plate of glass. The light from an electric lamp or a lime light is then directed on the surface of *L*, which is gradually lowered until the rings appear. The length of the bar *B* is then noted and the temperature is determined at the same time. The temperature of the whole is then raised, and again noted, together with the corresponding length of the bar. By dividing the difference in length by the difference in temperature at the two observations the coefficient of expansion is obviously found, provided that the expansion of the supports is known and duly regarded in the calculation.

57. **Determination of cubical expansion.**—When the coefficient of linear expansion of a substance is known, its coefficient of cubical expansion is obtained by multiplying the linear coefficient by 3, as already explained. The cubical expansion can also be ascertained by direct measurement. The following method was employed by Dulong and Petit for this purpose. Into a glass tube, 18 millimetres wide and 6 decimetres long, and closed at one end, they introduced a rod, previously weighed, of a metal not attacked by mercury. Let w' be its weight. The tube was then drawn out at the open end and bent as in the weight thermometer, *fig.* 22, after which it was filled with pure mercury, and boiled out to remove every trace of air, exactly as in filling a mercurial thermometer. In this state the apparatus was placed horizontally and surrounded with melting ice, the point dipping below the surface of mercury contained in a small capsule. It was thus filled with mercury at 0° . The capsule was next emptied, replaced under the point, and the apparatus allowed again to assume the temperature of the atmosphere. Then, by weighing together the tube and capsule, and deducting from the gross weight their weight before the introduction of the mercury, they obtained the weight, w , of the mercury which exactly filled at 0° so much of the capacity of the tube as was not occupied by the metal rod. The experiment was completed by heating the instrument in an oil-bath to a high temperature, t , and weighing the quantity which escaped from the point, as in the determination of a temperature by means of the weight thermometer.

If D_0 and D_0' represent the densities at 0° of mercury and of

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the metal; Δ , α , and κ , the coefficients of cubical expansion of mercury, of the metal, and of glass respectively, their volumes at 0° will be represented by

$$\frac{w}{D_0}, \frac{w'}{D'_0}, \text{ and } \left(\frac{w}{D_0} + \frac{w'}{D'_0} \right);$$

and if w is the weight of mercury which escapes from the tube between 0° and t° , the weight of mercury remaining in the tube at the latter temperature will be $w - w$. Then putting the volume of this weight of mercury at the temperature t , together with that of the metal rod at the same temperature, equal to the capacity of the tube which contains them, we have

$$\begin{aligned} \frac{w-w}{D_0} (1 + \Delta t) + \frac{w'}{D'_0} (1 + \alpha t) &= \left(\frac{w}{D_0} + \frac{w'}{D'_0} \right) (1 + \kappa t); \\ \alpha &= \frac{w D'_0}{w' D_0} + \frac{D'_0}{w'} \left\{ \left(\frac{w}{D_0} + \frac{w'}{D'_0} \right) \kappa - \left(\frac{w-w}{D_0} \right) \Delta \right\} \end{aligned}$$

It is of course necessary that the values of Δ and κ should have been determined by previous experiments in the way already described.

Another, to some extent similar, method of measuring the cubical expansion of solid bodies consists in determining their specific gravities at various temperatures, the bulk of a given weight of a substance being inversely as its density.

In applying this method, the weight of water free from air which fills a specific-gravity bottle at various temperatures is first ascertained; then the weight of the bottle is determined at the same temperatures after a known weight of the substance under examination has been put into it, and the interstices filled with water. Let w be the weight of water which fills the bottle at the temperature t , w' the weight of the solid substance, and s the weight of water and solid substance which together fill the bottle at t° ; then the density of the substance at t° , compared with that of water at the same temperature, is $D = \frac{w'}{w - (s - w')}$; and if v_1 represents the bulk which a unit-volume of water measured at 0° assumes at t° , the density of the substance at t° , compared with that of water at 0° , is $\frac{D}{v_1} = D_0$.

Lastly, if the density D'_0 of the substance at some other temperature t'° , has been determined in the same way, its mean coefficient of cubical expansion for one degree between t° and t'° is $\frac{D_0 - D'_0}{(t' - t) D'_0}$.

Table of Coefficients of Cubical Expansion of Solids for 1° C.

Substance	Coefficients	Interval of Temperature	Observer
Glass	$\alpha_{1770} = 0.0000258$	0 to 100	Dulong
"	$\alpha_{1770} = 0.0000275$	0 " 200	"
"	$\alpha_{1770} = 0.0000304$	0 " 300	"
Soft French glass	"0000260	17 " 99	Kopp
" " another kind	"0000253	7 " 99	"
Hard potash glass	"0000209	16 " 100	"
Common glass	$\alpha_{1770} = 0.0000276$	0 " 100	Regnault
"	$\alpha_{1770} = 0.0000305$	0 " 300	"
Crystal Glass from Choisy-le-Roi	$\alpha_{1770} = 0.0000228$	0 " 100	"
"	$\alpha_{1770} = 0.0000233$	0 " 300	"
Iron	$\alpha_{1770} = 0.0000355$	0 " 100	Dulong
"	$\alpha_{1770} = 0.0000441$	0 " 300	"
" (soft wire)	"0000370	13 " 100	Kopp
Copper	$\alpha_{1770} = 0.0000515$	0 " 100	Dulong
"	$\alpha_{1770} = 0.0000565$	0 " 300	"
" (wire)	"0000518	11 " 99	Kopp
Platinum	$\alpha_{1770} = 0.0000265$	0 " 100	Dulong
"	$\alpha_{1770} = 0.0000275$	0 " 300	"
Lead	"0000889	11 " 100	Kopp
Tin	"0000689	12 " 99	"
Zinc	"0000893	11 " 44	"
Cadmium	"0000936	12 " 43	"
Bismuth	"0000400	12 " 41	"
Antimony	"0000352	12 " 43	"
Sulphur	"0001826	14 " 46	"
Lead glance	"0000680	14 " 48	"
Zinc-blende	"0000358	15 " 45	"
Iron-pyrites	"0000338	15 " 47	"
Rutile	"0000322	14 " 46	"
Tin-stone (SnO ²)	"0000163	16 " 46	"
Specular iron	"0000404	13 " 47	"
Magnetic iron ore	"0000291	17 " 50	"
Fluor-spar	"0000623	14 " 47	"
Aragonite	"0000647	10 " 43	"
Calc-spar	"0000175	9 " 42	"
Bitter-spar	"0000352	13 " 43	"
Spathic iron ore	"0000350	14 " 45	"
Heavy spar	"0000581	12 " 42	"
Cœlestine	"0000608	12 " 45	"
Orthoclase	"0000225	13 " 99	"
Quartz	"0000403	18 " 100	"
Bayeux porcelain	"0000108	0 " 860	Déville and Troost
"	"0000108	0 " 1000	"

The cubical expansion of a considerable number of crystallised compounds has also been determined by Youle and Playfair (Chem. Soc. Qu. J. i. 121; for a table of the results see also Gmelin's Handbook, i. 234).

58. Variation of the coefficients of expansion depending on the temperature.—From the determinations given at the beginning of this table, it will be seen that the coefficients of expansion of solid bodies become greater as the temperature rises; but that the coefficient of expansion of platinum, which

at the temperatures of the experiments is very far from the point at which fusion or softening occurs, increases much less than the co-efficients of expansion of the more fusible metals, copper and iron. The rule thus indicated has been found to be verified in other cases, viz., that with solids the co-efficients of expansion remain sensibly constant at temperatures far removed from those at which change of state occurs, and vary more and more rapidly as these latter temperatures are approached. In general it is found that solid bodies suffer an almost uniform rate of dilatation through a range of temperature extending from 0° to 100° , that is to say, the increments of volume which attend each degree of temperature which the body receives are equal. If, therefore, the entire increment of volume which such a body undergoes when it is raised from 0° to 100° be divided by 100, the quotient will be the increment of volume which it receives when its temperature is raised one degree. On the other hand, when solids are elevated to temperatures much above 100° , and more especially when they approach those temperatures at which they would be fused or liquefied, the dilatations are not uniform. As the temperature is raised, the rate of dilatation is increased, that is to say, a greater increment of volume attends each degree of temperature.

59. Expansion of crystals.—The expansion of amorphous solids and of those which crystallise in the regular system is the same for all dimensions, unless when they are subject to a mechanical strain in some particular direction. A fragment of such a substance varies in bulk with variations of temperature, but retains always the same shape.

Crystals not belonging to the regular system exhibit when heated an unequal expansion in the direction of their axes, in consequence of which the magnitude of their angles becomes altered. In crystals belonging to the trimetric system, the expansion is different in the direction of all three axes; in aragonite, on raising the temperature from 0° to 100° , the inclination of the lateral faces increases by $2' 46''$, and that of the terminal faces diminishes by $5' 29''$; gypsum is, according to *Fresnel*, more expanded by heat in the direction of the principal axis than in that of the lateral axes. In crystals belonging to the hexagonal system, the expansion is the same in the directions of the three secondary axes, but different from that according to the principal axis. The obtuse angles of the primitive rhombohedron of calespar diminish by $8\frac{1}{4}'$ when the crystal is heated 100° , and the acute angles increase by the same quantity. Hence *it may be calculated* that the relative expansion of the principal

axis (compared with that of the secondary axes) amounts to 0'00342; moreover, since, according to Mitscherlich and Dulong, the cubical expansion of calcspar between 0° and 100° is only 0'001961, it may likewise be determined that calcspar when thus heated does not expand in the direction of the secondary axes, but *contracts* by 0'00056, and that the absolute expansion of the principal axis may be estimated at 0'00286. In bitterspar, the obtuse angle of the primitive rhombohedron diminishes when the temperature is raised from 0° to 100° by 4' 6"; in ferruginous bitterspar by 3' 29"; in ironspar, containing a considerable quantity of manganese, by 3' 31", and in pure ironspar by 2' 22". Since now, among all these minerals, calcspar forms the least, and ferruginous bitterspar the most obtuse rhombohedron, it follows that the expansion in the direction of the principal axis does not increase in the same proportion as the relative length of the axis itself diminishes. (Mitscherlich).

The following direct determinations of the linear expansion of several crystallised substances, between 0° and 100°, made by Pfaff (Jahresber. 1858, 7), show very distinctly the inequality in the amounts of expansion in the direction of the different axes.

Linear Expansion of Crystals between 0° and 100°.

Monometric Crystals		Dimetric or Hexagonal Crystals		
Substance	Expansion	Substance	Expansion	
Garnet . . .	0'0008478	Tin-stone . . .	Principal Axis 0'0004860	Secondary Axis 0'0004526
Iron pyrites . .	'0010084	Vesuvian . . .	'0007872	'0009629
Magnetic iron . .	'0009540	Zircon . . .	'0006264	'0011054
Lead-glance . .	'0018594	Beryl . . .	'0001721	-0'0000132
Fluor-spar . .	'0019504	Corundum . . .	'0006876	'0006551
		Quartz . . .	'0008073	'0015147
		Tourmaline . .	'0009369	'0007732
		Calc-spar . .	'0026261	-0'0003105

NOTE.—A minus sign (—) in the last column denotes contraction instead of expansion.

This alteration of shape caused by change of temperature is most easily rendered evident in gypsum, of which substance twin-crystals often occur, having pretty nearly the form shown in *fig. 26*. From such a crystal, a portion, *abcd*, is cut, so that the new surfaces are perpendicular to the surface of combination, *mn*, of the two halves of the crystal, and the face, *ab*, is ground and polished. At the temperature of the atmosphere,

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this surface then constitutes a single unbroken plane ; but when it is heated to about 60° or 80° C., the shape of the crystal alters in the manner shown in *fig. 27*, and now parallel rays of light falling on the two halves from a distant object are reflected in different directions, so that two distinct images of the object may be seen simultaneously by reflection from the surface *a b*.

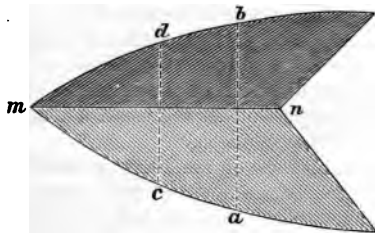


Fig. 26.

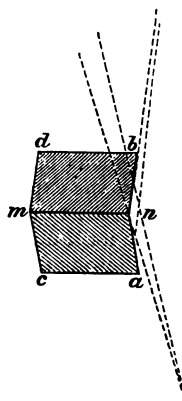


Fig. 27.

60. Exceptions of the general law of expansion.—One or two solid bodies are known which, at least within certain limits of temperature, form exceptions to the general rule of expansion by heat, and contract as their temperature is raised. For example, the alloy of 2 parts bismuth, 1 part tin, and 1 part lead, expands when heated from 0° to 44° C. ; when still further heated it contracts, so that at 56° its density is the same as it was at 0° , and at 69° still greater ; beyond this temperature expansion again takes place, at 87.5° the alloy has once more the same density as at 0° , and at 94° , at which it fuses, the same as at 44° .

Again, a piece of vulcanised caoutchouc, which is stretched by a weight to double its length, is shortened by a tenth when its temperature is raised 50° C., and the shortening effect increases rapidly with the stretching weight employed. (Youle, 'Proc. Roy. Soc.' viii. 356).

CHAPTER IV.

THE EXPANSION OF LIQUIDS.

61. **The liquid state.**—The liquid state is one of transition between the solid and the vaporous states. Solids by heat are converted into liquids, and liquids into vapours.

The liquid state, therefore, is maintained between two limits of temperature; a lower limit, at which the liquid would solidify, and a higher limit, at which it would vaporise. In different liquids these limits are separated by a greater or less range of temperature. In some, alcohol for example, the point of solidification stands at a very low temperature on the scale; while in others, as in some of the oils, the point of vaporisation is placed at a very high limit. In others, as in mercury, these points are widely separated, the vaporising point being at a very high, and the freezing point at a very low temperature.

It is found in general that the rate of dilatation of liquids is not uniform, like that of solids and gases, and that it not only increases as the temperature is elevated, but is subject to certain irregularities as it approaches the points at which the liquid would pass, on the one hand, into the solid, and, on the other, into the vaporous state.

Since by dilatation and contraction the proportion of the volume of the liquid to its weight is varied, all the methods which have been explained in the treatise on 'HYDROSTATICS,' page 74, &c., for ascertaining the specific gravity of liquids, will be equally applicable to determine their dilatation and contraction. If, for example, a given volume of liquid at a certain temperature weigh 1,000 grains, and the same volume at another temperature weigh only 950 grains, the proportion of the volumes which have equal weights will be the inverse of those numbers, that is, of 950 to 1,000.

The only body in the liquid state whose variations of volume through a considerable range of the thermometric scale are found to be very nearly exactly proportional to its change of temperature is mercury.

It has been ascertained that, from 0° to 100° , the increments of volume in this liquid for equal increments of temperature are very nearly equal.

The most important liquids whose rates of dilatation have

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been submitted to exact experimental investigation are water, mercury, and alcohol. The approximate increment of volume which each of these liquids receives from 0° to 100° is $\frac{1}{25}$ rd of the volume at 0° for water, $\frac{1}{55}$ th for mercury, and $\frac{1}{5}$ th for alcohol.

62. Apparent and absolute expansion.—An obvious method of determining the expansion of a liquid would clearly consist in observing how many divisions of a vessel graduated into parts of equal capacity are filled by the same weight of it at various temperatures. Such a method, however, would only be exact if the capacity of the containing vessel were known, not merely at some one temperature, but at each temperature at which an observation of the liquid was made. Thus it would be inaccurate to conclude that the expansion of a liquid between 0° and 100° amounted to 1 per cent. because the same quantity which filled 100 divisions at the former temperature occupied 101 divisions at the latter; for it is impossible to raise the temperature of a liquid without at the same time raising the temperature and so altering the capacity of the vessel in which it is contained. It is therefore necessary to distinguish between the *apparent* expansion of liquids, or that which would result from observations made in the manner that has been described, without taking account of the changes of capacity of the containing vessel, and the real or *absolute* expansion, which is the apparent expansion corrected for the simultaneous expansion of the vessel. In a similar manner, in increasing the changes of volume of gaseous bodies, the expansion of the containing vessel requires to be taken into account; but since the expansion of gases is much more considerable than that of any solid, the correction required is in the case of gases of much less relative consequence than it is in the case of liquids: thus, for example, the apparent expansion of air in a glass vessel would only differ from its real expansion about in the proportion of 140 : 141; whereas, in the case of mercury, the difference would amount to one-seventh of the total effect to be observed.

63. Relation between the absolute and apparent expansion.—From what has been already said, it will be evident that the apparent expansion of a liquid is equal to its absolute expansion for the same interval of temperature diminished by the corresponding expansion of the containing vessel. That is, if Δ be the coefficient of absolute expansion of a liquid, and δ its coefficient of apparent expansion, the relation between these two quantities will be the following, if κ is the coefficient of cubical expansion of the material of the vessel:—Let us suppose *that a vessel contains some liquid, and that both the liquid and*

the vessel have had their temperature raised from 0° to 1° . If v is the original volume of the liquid at 0° , and v' the original volume at 0° of that part of the vessel which is at 1° occupied by the liquid, since the *real* volumes of the liquid and the vessel at 1° are respectively $v(1 + \Delta)$ and $v'(1 + \kappa)$, we have—

$$v(1 + \Delta) = v'(1 + \kappa),$$

or

$$\frac{v' - v}{v} = \frac{\Delta - \kappa}{1 + \kappa}$$

But $v' - v$ is the apparent increase of volume of the liquid from a rise of temperature of one degree, and hence $\frac{v' - v}{v}$ is the coefficient of apparent expansion, δ . Accordingly,

$$\delta = \frac{\Delta - \kappa}{1 + \kappa}$$

or

$$\Delta = \delta + \kappa + \delta\kappa,$$

But as δ and κ are always small fractions, we may disregard their product $\delta\kappa$, and put

$$\Delta = \delta + \kappa,$$

that is, *the coefficient of absolute expansion of a liquid is equal to its coefficient of apparent expansion in a vessel of any material, together with the coefficient of cubical expansion of the material of which the vessel is made.*

64. **Methods of determining the expansion of liquids.**—

The first condition to be fulfilled in determining the coefficient of expansion of a liquid is accordingly that the capacity of the vessel which contains it is accurately ascertained. By far the most precise method of measuring the capacity of a vessel, and of finding the relative values of divisions which may be marked upon it, is to determine the weight of mercury which fills it up to the zero-point of the scale, and also the weight which corresponds to the intervals between any two divisions. But since both the capacity of the vessel and the specific gravity of mercury vary with variations of temperature, the different weights of mercury which fill the vessel at different temperatures do not at once enable its relative capacities at these temperatures to be calculated; for this it is necessary that the absolute expansion of mercury should be previously known. Hence the absolute expansion of mercury (which, on account of its inalterability and its property of not wetting glass, is better adapted for measuring purposes than any other liquid) is a necessary prelimi-

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nary datum for the determination of the absolute expansion of liquids in general.

65. Determination of the absolute expansion of mercury.—It is evident that, in order to obtain a trustworthy determination of this constant, some method must be devised whose results are wholly unaffected by changes in the capacity of the vessel in which the mercury is contained. A satisfactory solution of this apparently very difficult problem was first given by *Dulong* and *Petit*. Their method consisted in increasing the heights of columns of mercury at different temperatures, which produced equilibrium with another column of the same liquid at constant height, and kept always at 0° .

If h denotes the height of the column at 0° , d the density of mercury at 0° , h' the height of the column at t° , which produces equilibrium with the first, and d' the density of mercury at t° , we have (see 'HYDROSTATICS,' Article 34)—

$$\frac{h'}{h} = \frac{d}{d'}$$

Representing by v and v' the columns of the same weight of mercury at 0° and t° , we get—

$$\frac{d}{d'} = \frac{v'}{v}, \text{ hence } \frac{v'}{v} = \frac{h'}{h}$$

The mean coefficient of expansion between 0° and t° is therefore

$$\delta_t = \frac{v' - v}{v} = \frac{h' - h}{h}$$

and its determination requires only that the difference of height of the two columns, and the absolute height of the column at 0° , should be accurately measured.

The apparatus employed by *Dulong* and *Petit* consisted of a kind of inverted glass syphon, *fig.* 28, the two vertical branches of which, A and B, were about 0.55 metre long, and communicated below by a horizontal tube of very small diameter. The branch A was surrounded by a cylinder of tinned iron, which was kept full of ice; the other branch, B, occupied the middle of a covered cylindrical copper vessel filled with oil and built into a furnace. The quantity of mercury in the apparatus was so adjusted that the reservoir in the tube B was a little above the cover of the oil-bath, and the difference in the height of the two columns was measured by a cathetometer, that is, a horizontal telescope, capable of sliding along a vertical scale, and having a horizontal thread fixed across its axis. The temperature of the oil-bath was indicated by an air thermometer and a mercu-

rial weight thermometer, the reservoirs of which were of the same length as the mercury column in the tube B, and were placed near to and parallel with it.

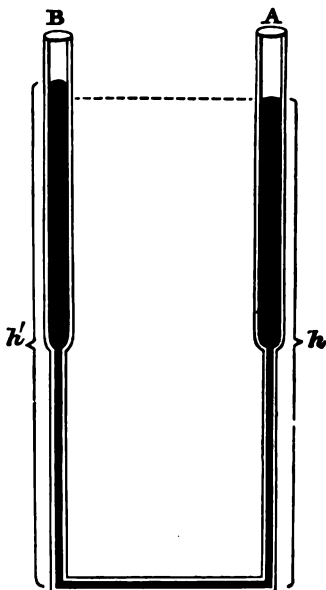


Fig. 28.

The following table gives the general results of a great number of determinations made with this apparatus :—

Absolute Expansion of Mercury (Dulong and Petit).

Temperature by the air- thermometer	Mean coefficient of expansion counted from 0°		
	Maximum value	Minimum value	Mean values
100°	1117	1117	1115 = 0.00018018
200°	1115	1131	1143 = 0.00018433
300°	1165	1165	1165 = 0.00018868

66. **Regnault's determination.**—The results of the experiments made by Dulong and Petit are affected by some sources of error, which cannot be considered as immaterial. The chief

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of these are, the uncertainty of the determinations of the temperature of the heated column, arising from various causes, and the comparative shortness of the two mercury-columns, whereby a very small absolute error in the measurement of h and h' comes to have a considerable effect on the value of the fraction $\frac{h' - h}{h} = \delta$.

In order to obtain results which should be, as far as possible, free from the errors thus arising, *Regnault* repeated the determination of the absolute expansion of mercury. His method is similar in principle to that of *Dulong* and *Petit*, but somewhat different in execution. The principle of the arrangement will be intelligible from *fig.* 29. AB and CD are two iron tubes, 1·5

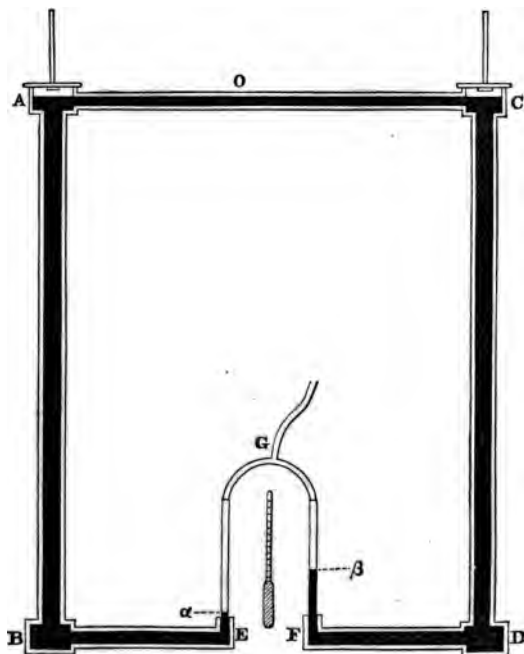


Fig. 29.

metre long and 10 mm. in internal diameter, connected above by the horizontal iron tube AC , of 2·5 mm. internal diameter, and respectively communicating below with the horizontal tubes

BE and **DF**, likewise of 2·5 mm. diameter, which in their turn carry vertical glass tubes at **E** and **F**. The apparatus having been adjusted so that the tubes **AB** and **CD** are exactly vertical, and the tubes **AC**, **BE**, and **DF** exactly horizontal, mercury is poured into it through one of the short tubes, open at both ends, by which both **AB** and **CD** are surmounted, and in proportion as the liquid rises in the vertical glass tubes at **E** and **F**, air is compressed into a copper receiver communicating with them by the leaden pipe **G**, so as to keep the level of the mercury near the bottom of the glass tubes. The addition of mercury is continued until it begins to run out of a hole, **O**, bored in the upper side of the tube **AC**. The vertical tube **AB** is placed in the centre of an oil-bath; **CD** is surrounded by a constant current of cold water.

On heating the tube **AB**, the density of the mercury in it was of course diminished, and consequently equilibrium of pressure in the tubes **EG** and **FG** could only be maintained by the sinking of the mercury-column in the former. The elastic force of the compressed air in the receiver was therefore balanced on the one hand by the pressure of the heated column of mercury of the height **AB**, = **H**, diminished by that of the column in **E**, = **h**; on the other hand, by the pressure of the cold column **CD** = **H'**, diminished by that of the column in **F**, = **h'**. The temperature of the column **AB** was indicated by an air-thermometer, that of **CD** by three mercurial thermometers in the water-vessel which surrounded it, and that of the mercury at **E** and **F** by a thermometer placed between them, as shown in the figure. When the necessary corrections for the differences of temperature of the several mercury-columns had been applied, the formula for the absolute expansion became—

$$\frac{(H' - h') - (H - h)}{H' - h'} = \delta.$$

But since the required corrections involved the knowledge of the very coefficient sought, the calculation could only be made by the method of successive approximations, that is, Dulong and Petit's coefficient was first assumed, in order to calculate an approximate result; then the number so obtained was substituted for the old coefficient, and so a still more accurate result was arrived at.

In another series of experiments, the tubes **AB** and **CD** were connected at the bottom by a continuous horizontal tube, and the tube **AC** was cut across, vertical glass tubes being inserted into the two halves, wherein the different heights attained by the mercury-column could be observed. In this state the ap-

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paratus was merely a modified form of that employed by Dulong and Petit.

The results ultimately arrived at are given in the following table, the temperatures in the first column of which are those measured by the air thermometer.

Absolute Expansion of Mercury (Regnault).

Temperature = t	Volume at t°	Mean coefficient of expansion between 0° and t°	True coefficient of expansion at t°
0	1'000000	0'0000000	0'00017905
10	1'001792	0'00017925	0'00017950
20	1'003590	0'00017951	0'00018001
30	1'005393	0'00017976	0'00018051
40	1'007201	0'00018002	0'00018102
50	1'009013	0'00018027	0'00018152
60	1'010831	0'00018052	0'00018203
70	1'012655	0'00018078	0'00018253
80	1'014482	0'00018102	0'00018304
90	1'016315	0'00018128	0'00018354
100	1'018153	0'00018153	0'00018405
110	1'019996	0'00018178	0'00018455
120	1'021844	0'00018203	0'00018505
130	1'023697	0'00018228	0'00018556
140	1'025555	0'00018254	0'00018606
150	1'027419	0'00018279	0'00018657
160	1'029287	0'00018304	0'00018707
170	1'031160	0'00018329	0'00018758
180	1'033039	0'00018355	0'00018808
190	1'034922	0'00018380	0'00018859
200	1'036811	0'00018405	0'00018909
210	1'038704	0'00018430	0'00018959
220	1'040603	0'00018456	0'00019010
230	1'042506	0'00018481	0'00019061
240	1'044415	0'00018506	0'00019111
250	1'046329	0'00018531	0'00019161
260	1'048247	0'00018557	0'00019212
270	1'050171	0'00018582	0'00019262
280	1'052100	0'00018607	0'00019313
290	1'054034	0'00018632	0'00019363
300	1'055973	0'00018658	0'00019413
310	1'057917	0'00018683	0'00019464
320	1'059866	0'00018708	0'00019515
330	1'061820	0'00018733	0'00019565
340	1'063778	0'00018758	0'00019616
350	1'065743	0'00018784	0'00019666

67. **Results of the preceding table.**—The numbers in the last column represent amounts by which a unit volume of mercury expands for a rise of temperature of one degree Centigrade at various temperatures between 0° and 350° . Thus, 100,000,000

cubic millimetres of mercury, measured at 0° , occupy 100,017,905 cubic millimetres at 1° ; 100,000,000 cubic millimetres, measured at 300° , become 100,019,413 cubic millimetres at 301° .

Accordingly, the *true coefficient of expansion increases as the temperature rises.*

The third column contains the quotients obtained by dividing the difference between the volume (v.) of mercury at t° and the volume of the same weight at 0° ($v_0 = 1$) by the number of degrees of temperature ($= t$), that is to say, the column exhibits the *mean co-efficients of expansion between 0° and t° , viz. :*

$$\frac{v - 1}{t}$$

Between 0° and 100° the mean coefficients vary so little that the real expansion of mercury, and much more, therefore, its apparent smaller expansion in glass, may be taken as proportional to the true increase of temperature.

68. Apparent expansion of mercury and cubical expansion of glass vessels.—By the help of the foregoing table of the absolute expansion of mercury, the cubical expansion of glass vessels may be determined. For this purpose the neck of the vessel is drawn out to a capillary point; it is filled with mercury, care being taken to exclude all moisture or air, exposed successively to the temperatures 0° and 100° , and weighed with the quantity of mercury which fills it at each of these temperatures. Let

the weight of the empty glass vessel be = w ,
the weight of the vessel filled with mercury at 0° = w ,
the weight of the vessel filled with mercury at 100° = w' ,
let Δ be the absolute expansion of mercury, and κ the cubical expansion of glass between 0° and 100° , then we have

$$\frac{w - w}{w' - w} = \frac{1 + \Delta}{1 + \kappa} \text{ and therefore } \kappa = \frac{w' - w}{w - w} (1 + \Delta) - 1.$$

When once the cubical expansion of a glass vessel is known, the absolute expansion of any liquid can be deduced in the manner already explained (Art. 63) from its apparent expansion as observed in this vessel. Hence a problem of frequent occurrence is to determine the expansion of the glass of a vessel shaped like a thermometer, and provided with a divided stem,* for which the relative capacities of the bulb and of one division of the stem have been previously determined. In such a case it is only necessary to fill the apparatus to some particular point of the scale with well-boiled mercury, and to observe the apparent volumes

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of the mercury, v and v' , at 0° and 100° , expressed in divisions of the scale ; the expansion of the glass can then be calculated. For the apparent volume of the mercury at 100° is equal to its volume at 0° increased by the amount of its absolute expansion between 0° and 100° , that is

$$v' (1 + \kappa) = v (1 + \Delta) \text{ or } \kappa = \frac{v}{v'} (1 + \Delta) - 1.$$

The apparent expansion of mercury in glass varies with the kind of glass employed, but may be taken on an average = 0.0001545 for each degree Centigrade. This value may be used, for instance, without hesitation in calculating the corrected length of the portion of the thread of mercury in a thermometer which is not exposed to the temperature that is to be measured (see below, Determination of boiling points). Between 0° and 100° the apparent volume of mercury in glass increases in the proportion of $1 : 1.01545$; while the real volume increases in the proportion of $1 : 1.01815$, hence the cubical expansion of glass is

$$\kappa = \frac{1.01815}{1.01545} - 1 = 0.002663.$$

Another case in which the absolute expansion of mercury requires to be taken into account is in reducing barometric observations to 0° C .

69. Expansion of other liquids.—The absolute expansion of any liquid can now be ascertained by filling with it a small glass bottle, whose cubical expansion has been previously ascertained in the manner already described, and weighing the bottle with the quantity of liquid which fills it at different temperatures. But a more rapid method, and, therefore, one more frequently adopted, is to observe the apparent expansion of the liquid in a *dilatometer*, an instrument shaped just like a common mercurial thermometer, and then to correct these observations for the previously known cubical expansion of the glass. In this way very numerous determinations have been made by *Isidore Pierre* and *Herman Kopp*. The results of these investigations are given in the following table for a few of the more important liquids :—

Total apparent expansions between 0° and 100° C .

Distilled water	0.0466	Alcohol	0.11
Water saturated with salt	0.05	Benzine	0.118
Sulphuric acid	0.06	Di-sulphide of carbon	0.114
Hydrochloric acid	0.06	Bromine	0.103
Oil of turpentine	0.084	Acetic acid	0.105
Ether	0.148	Chloroform	0.111
Nitric acid	0.11	Olive oil	0.073

70. **The expansion of water.**—Water, as it falls in temperature towards the freezing point, exhibits phenomena which form a striking exception to the general laws of dilatation and contraction by temperature. As its temperature is lowered, the rate at which it contracts is found to diminish until it arrives at the temperature of 4°C ., when all contraction ceases, and, if the temperature be further lowered, the volume is observed to remain stationary for some time ; but, on lowering it still more, instead of contraction, a dilatation is produced, and this dilatation continues at an increasing rate until the water is congealed. It appears, therefore, that at the temperature of 4° the density of water is a maximum. It is found that for a few degrees above and below such temperature of greatest density the dilatation is the same ; thus, at 1° above and 1° below 4° and at 2° above and 2° below that point, the specific gravities are almost exactly equal.

The experiments of *Hüllström* fixed the temperature of the minimum density of water at $3^{\circ}.90$. *Despretz* found it in one series of experiments, made by a water thermometer at $4^{\circ}.007$; by another method he found it to be $3^{\circ}.997$. *Youle* and *Playfair* fixed it at $3^{\circ}.945$, *Kopp* at $4^{\circ}.08$, *Rosetti* at $4^{\circ}.07$. The mean of these results is $3^{\circ}.965$, or very nearly 4° , which is the temperature of maximum density adopted in fixing the French standard of weight.

Water, at its greatest density, is taken as the base of the uniform system of measures adopted in France, the unit of weight being the weight of a cube of distilled water taken at its greatest density, the side of the cube being the length of a centimetre, or the one-hundredth part of a metre, which is the linear unit. The length of the metre is $39\frac{37}{1000}$ English inches.

The weight of one cubic centimetre of water at 4° is called a *gramme* : it is equal to $15\frac{45}{1000}$ English grains.

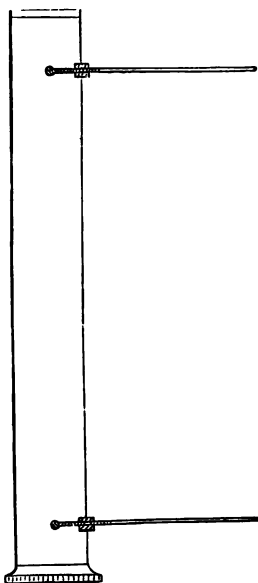


Fig. 30.

71. **Experimental proof of Erman and Hope.**—This

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method of determining the maximum density of water was employed by *Erman*, and in a modified form by *Hope*. A deep vessel, *fig. 30*, is perforated by two lateral apertures, in which thermometers are fixed. Suppose at first a vessel of this kind to be filled with water at 0° and placed in a room in which the temperature of the air is, for example, at 15° . The layer of the liquid at the side of the vessel becomes heated, and we should expect the upper thermometer to rise first, if water did not present the anomaly of being most dense at 4° . What actually happens is that the lower thermometer rises gradually to 4° , in consequence of the descent of the heated particles of water, while the upper thermometer remains still at zero. It follows that water at 4° is heavier than water between 0° and 4° . The converse of the experiment proves the same fact. The vessel being filled with water at 15° is placed in a room at zero; in this case the lower thermometer sinks to 4° and remains stationary for some time, while the upper thermometer cools down until it reaches zero.

72. **Other methods of determining the maximum density of water.**—*Hüllström's* method consisted in weighing a glass bulb, loaded with sand, in water at different temperatures. Allowing for the expansion of glass, he found that the bulb lost most weight in water at 4° , and that consequently this was the temperature of the maximum density of water.

Despretz took a water thermometer, that is to say, a bulbéd tube containing water, and placing it in a bath, the temperature of which was indicated by an ordinary mercury thermometer, he found that the water contracted to the greatest extent at 4° , and that this is therefore the point of greatest density.

The same method was followed by *Kopp* for determining the behaviour of water between 0° and 100° , with the following results :—

Expansion of water (Kopp).

Temperature.	Volume (Volume at $0^{\circ}=1$)	Density (Density at $0^{\circ}=1$)	Volume (Volume at $4^{\circ}=1$)	Density (Density at $4^{\circ}=1$)
0	1'00000	1'000000	1'00012	0'999877
1	0'99995	1'000053	1'00007	0'999930
2	0'99991	1'000092	1'00003	0'999959
3	0'99989	1'000115	1'00001	0'999992
4	0'99988	1'000123	1'00000	1'000000
5	0'99988	1'000117	1'00001	0'999994
6	0'99990	1'000097	1'00003	0'999973

Expansion of water (Kopp)—continued.

Temperature.	Volume (Volume at 0°=1)	Density (Density at 0°=1)	Volume (Volume at 4°=1)	Density (Density at 4°=1)
7	0'99994	1'000062	1'00006	0'999939
8	0'99999	1'000014	1'00011	0'999890
9	1'00005	0'999952	1'00017	0'999829
10	1'00012	0'999876	1'00025	0'999753
11	1'00021	0'999785	1'00034	0'999664
12	1'00031	0'999686	1'00044	0'999562
13	1'00043	0'999572	1'00055	0'999449
14	1'00056	0'999445	1'00068	0'999322
15	1'00070	0'999306	1'00082	0'999183
16	1'00085	0'999155	1'00097	0'999032
17	1'00101	0'998992	1'00113	0'998869
18	1'00118	0'998817	1'00131	0'998695
19	1'00137	0'998631	1'00149	0'998509
20	1'00157	0'998435	1'00169	0'998312
21	1'00178	0'998228	1'00190	0'998104
22	1'00200	0'998010	1'00212	0'997886
23	1'00223	0'997780	1'00235	0'997657
24	1'00247	0'997541	1'00259	0'997419
25	1'00271	0'997293	1'00284	0'997170
26	1'00295	0'997035	1'00310	0'996912
27	1'00319	0'996767	1'00337	0'996644
28	1'00347	0'996489	1'00365	0'996367
29	1'00376	0'996202	1'00393	0'996082
30	1'00406	0'996008	1'00423	0'995787
35	1'00570			
40	1'00753			
45	1'00954			
50	1'01177			
55	1'01410			
60	1'01659			
65	1'01930			
70	1'02225			
75	1'02541			
80	1'02858			
85	1'03189			
90	1'03540			
95	1'03909			
100	1'04299			

73. Importance of the phenomenon in the economy of nature.—The fact that the maximum density of water is not at 0°, but at a higher temperature, is of great importance in the household of nature. In winter the temperatures of lakes and rivers falls, in consequence of their surface being in contact with the colder air, and also from other causes, such as radiation. The colder surface layer sinks to the bottom, and a continual series of currents goes on until the whole mass is at a temperature of 4°. Thence the cooling on the surface still continues, but

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the cooled layers being now lighter remain on the surface, and ultimately freeze. The ice formed thus protects the water below, which remains at a temperature of 4° , even in the most severe winters, a temperature at which fishes and other inhabitants of the waters are not destroyed.

74. Saline solutions.—If salts are dissolved in water, the freezing point is lowered, and the anomaly just described gradually disappears, that is, the temperature of maximum density approaches more and more to the freezing point of the mixture the more of the solid is dissolved in proportion to the water. In fact, the temperature of maximum density falls even more rapidly than the freezing point, so that for solutions containing a certain proportion of salt the temperature of maximum density is below their freezing point. It is obvious that in order to show this experimentally, the solution must be placed in circumstances which will be referred to further on, so as to remain liquid at a temperature below its freezing point. *Despretz* mixed different quantities of chloride of calcium with the same quantity of pure water, viz. 997·45 grammes, and obtained the following results :—

Quantity of Chloride of Calcium	Density	Temp. of Maximum density	Freezing point
Grammes			
0	1·000	$4^{\circ}00$	$0^{\circ}00$
6·173	1·005	$3^{\circ}24$	$-0^{\circ}38$
12·346	1·010	$2^{\circ}05$	$-0^{\circ}53$
24·692	1·020	$0^{\circ}06$	$-1^{\circ}12$
37·039	1·030	$-2^{\circ}43$	$-3^{\circ}92$
74·078	1·060	$-10^{\circ}43$	$-5^{\circ}28$

75. Effect of different density of the different strata in the same liquid.—It has been already proved that if liquids having different specific gravities be placed in the same vessel without mixing with each other they will arrange themselves in strata according to their specific gravities, the heavier being below the lighter. This principle will seem to explain several facts. If cold water be poured into a vessel, a thermometer being immersed in it, and hot water be carefully poured over it, so as to prevent the liquids being mixed, the hot water will float on the cold. The thermometer immersed in the cold water will not rise, nor will a thermometer immersed in the hot water fall. But if the water be agitated so as to mix the two strata, then their temperatures will be equalised and the lower thermometer will rise and the upper fall. If, however, hot water be

first poured into the vessel, a thermometer being immersed in it, and cold water be then carefully poured over it, so as to prevent such agitation as would cause the fluids to mix, and a thermometer be also immersed in it, it will be found that the lower thermometer will rapidly fall and the higher one will rise; in fact, in this case the cold water descends through the hot water by its superior gravity, and the two fluids of different temperatures, in passing through one another, become mixed, and the whole mass takes an intermediate temperature.

76. Process of heating a liquid.—The process by which water is boiled by heat applied to the bottom of a vessel is explained on this principle. The water in contact with the bottom of the vessel being heated, is expanded, and becomes lighter, bulk for bulk, than the strata over it. It therefore rises, and the water above it falls, and, in its turn being expanded by heat, is made to rise. There is thus a continual current of the water heated by the fire upwards, and a counter current of the colder water forming the superior strata downwards; and this goes on until all the water in the vessel has been raised to the boiling point. To this phenomenon the name of *convection* is given.

It is easy to show that any source of heat, however intense, applied to the upper surface of water, would be incapable of raising the temperature of the mass. Thus, if we suppose oil at the temperature of 120° poured upon the surface of water in a vessel at 10° , the oil will float upon the water, and a thin stratum of the water in contact with it will have its temperature raised, and will therefore be expanded; but, being lighter, bulk for bulk, than the colder water under it, it will still float on the top. No interchange of currents will take place, by which the heated water forming the upper stratum can be mixed with the water forming the lower stratum; and, as water is a bad conductor of heat, as will hereafter be shown, the heat of the oil, and the stratum of water in immediate contact with it, will not be propagated downwards. It would be possible for a lump of ice to remain in the bottom of such a vessel without being melted, notwithstanding the stratum of oil at 120° floating upon its surface.

77. Experimental proof.—The system of upward and downward currents produced by heat applied to the bottom of a vessel containing a liquid may be rendered manifest by the following experiment. Let a tall jar (*fig. 31*) be filled with cold water, and let some amber powder be thrown into it. The particles of this powder being equal in weight to water, bulk for

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bulk, or nearly so, will remain suspended, and may be seen through the sides of the vessel. Let this jar be immersed to some depth in a vessel of hot water, so that the lowest strata of the water in it may become gradually heated. The water in the bottom of the jar will now be observed continually to ascend, carrying the amber particles with it, while the colder water in the upper part will descend. The contrary currents will be rendered manifest to the eye by the particles of amber which they carry with them.

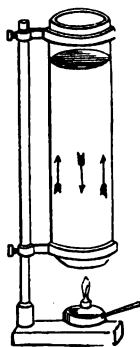


Fig. 31.

If heat be applied to the sides of the cylindrical jar, but not to the bottom, the water immediately in contact with the sides, becoming heated, will ascend. The water in the centre of the jar, on the other hand, being removed from the source of heat, will retain its temperature, and will of course sink as the water next the side rises. In this case, two distinct currents will be seen, one immediately next the surface of the jar continually ascending, and the other in the centre of the jar continually descending.

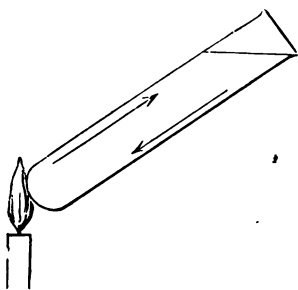


Fig. 32.

This may be shown by placing the cylindrical glass jar within another somewhat greater in diameter, and pouring a hot liquid in the space between them.

On a small scale the currents produced by convection may easily be observed by means of a test tube filled with water and held in the edge of a flame, as in *fig. 32*. The currents of heated water are shown by small

shreds of blotting-paper, a bit of which is rubbed down in a mortar with a few drops of water, and then thrown into the test tube.

78. Warming buildings by hot water.—A section of one of the forms of apparatus used for this purpose is shown in *fig. 33*. A furnace, *F*, is established in the basement, surrounded by a boiler *o o* of sufficient capacity. From the top of this boiler a pipe *a* proceeds vertically upwards to the bottom of a reservoir *B* established at the roof of the building. This reservoir is closed at the top, but is provided with a safety valve *c*,

which opens whenever the water in *B* produces steam which exceeds a certain pressure. From the bottom of the reservoir *B* two other tubes *D D* descend, which communicate by branches with lateral tubes leading into all the rooms to be warmed. After passing through all these, and being carried back by return pipes, the series of descending pipes terminates at the bottom of the boiler *o o* where they enter it.

Let us now suppose that water is poured into the reservoir *B* until the boiler *o o*, the entire series of pipes and reservoirs *a b*

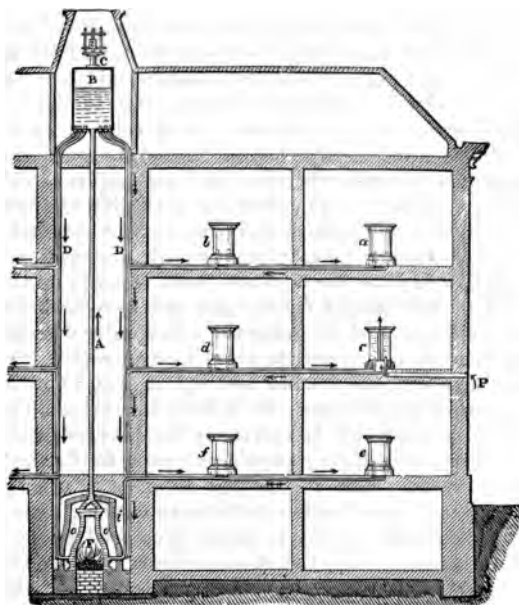


Fig. 33.

c d e f, placed in all the rooms to be warmed, and the reservoir *B*, shall be filled. If a fire be then lighted in a furnace *F*, a current of heated water will rise in the pipe *A*, and will be replaced by an equal quantity of cold water flowing in through the lateral pipes at the bottom of the boiler. In this way there will be a continual interchange of hot water sent upwards through *A*, and cold water flowing in through the lateral pipes, until the entire quantity of water filling the whole system of pipes and the reservoir *B* has attained a certain temperature.

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It will attain this limit of temperature so soon as the heat radiated from the surfaces of all the pipes becomes equal to the heat developed in the furnace *r*.

79. **Oceanic currents.**—Convection, caused by difference of density of the different strata of the sea, is probably the principal cause of the currents of the ocean. In fact, the sea is an enormous mass of liquid whose temperature varies from point to point. Equilibrium is consequently impossible, and the different parts must therefore be in a state of continual motion with regard to each other. The waters of the tropical seas should, by reason of their higher temperature, have a higher level than those of the polar seas; and the result is a continual kind of overflowing of the waters about the equator, and consequently a vast current setting towards the poles. But to this current evidently corresponds a lower current of cold water flowing towards the equator, there to become heated, to overflow again, and so on. In general, wherever we have waters of different temperatures or, what is the same thing, of different densities, there the lighter will ascend and the heavier descend; and wherever a deficiency takes place through evaporation, there water will flow in from the adjacent parts to make up the deficiency. But difference of density may also arise from different degrees of saltness, and wherever the salter water descends and flows off as an under current to some fresher region, there at the same time will the fresher and lighter water flow in from above to restore equilibrium. It is from this reason that the subject of ocean-currents is extremely complicated, and still a point of controversy among physicists: some attributing much to aerial currents, others to unequal densities as arising from different proportions of saline matter in solution; some to unequal densities as arising from polar and equatorial temperatures, and others again to restoration of equilibrium after certain areas have been exposed to high insolation and consequent evaporation. Any of these may act in different areas as initial force; but, generally speaking, unequal densities, whether arising from temperature or salinity, and evaporation by lowering the surface, are the main originators of the movements in the oceanic mass, however much these movements may be subsequently accelerated, retarded, or diverted by winds, by the configuration of coasts, or by inequalities of the sea-bottom.

CHAPTER V.

THE EXPANSION OF GASES.

80. **Dilatation of gases.**—It has been already shown in the treatise on 'HYDROSTATICS,' page 126, that the dimensions of bodies in the gaseous state are dependent altogether upon the pressure under which they are confined. They are capable of expanding spontaneously into any dimensions, however great, and of being reduced by greater pressure to any volume, however small. It follows, therefore, that whenever it is required to determine the change of dimensions of gaseous bodies produced by change of temperature, it will be necessary to provide means of keeping them during the experiment under a uniform pressure, since otherwise the change of dimensions due to change of pressure would be combined with that which is due to change of temperature.

Experimental enquirers have contrived and practised various expedients to accomplish this, one of the first and most simple of which was that originally due to M. Pouillet, represented in *fig. 34*.

An iron syphon tube *DC* is formed with short legs, from the bottom of which proceeds a pipe with a stop-cock *F*, under which is placed a cistern or reservoir *G*. In the legs of the syphon *DC* are inserted two glass tubes *DE* and *CB*, of more than thirty inches in height. The tube *DE* is open at the top; the tube *CB* is closed at the top, but has a horizontal branch united to it at *B*, which is connected with a tube *AB* made of platinum, which terminates in a hollow ball *A*, also of platinum. A stop-cock is provided in the tube *BA*, so as to communicate at pleasure with the external air. The stop-cock *F* being closed, and the stop-cock in the tube *BA* being open, mercury is poured into the tube *DE*, so as to fill the glass tubes *DE* and *CB* nearly to the top. Since the two tubes *DE* and *CB* both communicate with the external air, the columns of mercury in them will stand at the same level. To determine the expansion which air suffers

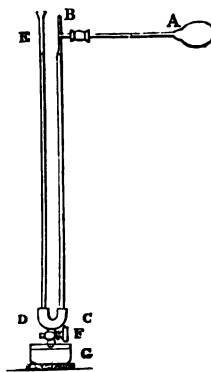


Fig. 34.

when raised from the freezing to the boiling point under a uniform pressure let the reservoir A be immersed in a bath of melting ice, so as to reduce the air included in it to the freezing point. Let the stop-cock in the tube BA be then closed, and let the bulb A be removed to a bath of boiling water. The air in the bulb, expanding, will press down the column of mercury in BC, and will cause the column in DE to rise; so that the levels of the two columns will no longer coincide. But they may be equalised by opening the stop-cock F, and allowing mercury to flow into the reservoir G from the syphon, until the levels in the two legs come to the same point. When that is accomplished, the pressure upon the expanded air included in the bulb A, and the tube communicating with it, will be equal to that of the atmosphere, and equal to that which the same air has when at the freezing point.

The capacity of the tube CB being known, the volume which corresponds to any length of it will be also known.

Now the increment of volume which the air has suffered by expansion will be indicated by the height through which the mercury has fallen in the tube CB. This increment, therefore, will be the dilatation of the air included in the bulb A and the communicating tube, between the freezing and boiling points.

In the same manner, by this apparatus, the dilatation corresponding to any change whatever of temperature under a given pressure can be ascertained.

81. Dilatation of all gases uniform.—It has been proved by experiments made with this, as well as a variety of other apparatus adapted to the same purpose, that the dilatation of all bodies in the gaseous form is *perfectly uniform throughout the whole extent of the thermometric scale*, the same increments of temperature producing, under the same pressure, equal increments of volume. But, what is still more remarkable, it has been found that *all gases whatever*, as well as all vapours raised from liquids by heat, *are subject to exactly the same quantity of expansion by the same change of temperature.*

82. Gay-Lussac's method of determining the expansion of gases.—The first tolerably accurate determinations of the coefficients of expansion of gaseous bodies were made by Gay-Lussac. He used in his experiments a vessel shaped much like a thermometer, having a bulb about 1 centimetre in diameter, and a tube about 30 or 40 centimetres long, and 1 or 1·5 millimetres wide. The tube was divided into lengths of equal capacity, and the proportion between the total capacity of the bulb and that of one division of the tube was accurately deter-

mined. The apparatus having been filled with air dried by passing through a chloride of calcium tube, a drop of mercury, occupying a short length of the divided tube, was employed to cut off the enclosed air from communication with the atmosphere, and at the same time to serve as an index whereby to read off its volume. The bulb was then fixed, with the stem horizontal and projecting through the side, in a vessel filled with water, through the medium of which it could be heated to various temperatures. The volumes occupied by the air at each temperature could be read off upon the divided tube by noting the position of the little column of mercury; but the volumes thus determined required to be corrected (*a*) for the expansion of the glass, (*b*) for the lower temperature of the portion of air contained in the part of the tube outside the water bath, and (*c*) for the possible alteration of barometric pressure during the experiment. Independently of these latter alterations, which were always very inconsiderable, the pressure upon the gas remained constant during the experiment: it was the volume that changed. Applying the same method to other gases and to vapour, Gay-Lussac concluded that all gases and vapours (at temperatures sufficiently removed from their points of liquefaction) expanded by heat to the same extent; that, namely, when heated from 0° to 100° C. they expanded in the proportion of 1 : 1.375, or for 1° C. by $0.00375 = \frac{1}{267}$ of their volume at 0° .

83. **Rudberg's researches.**—The experiments of Gay-Lussac, the results of which were in accordance with those subsequently obtained by Dulong and Petit, established the fact that all gases, as well as all vapours, undergo equal changes of volume by equal increments of temperature, the coefficients of the expansion of atmospheric air being common to all.

The confidence which these results naturally excited in consequence of the high reputation of the author was still further increased by the confirmation which they received at the hands of Dulong and Petit, and also because it was considered probable, on theoretical grounds, that in substances in which cohesive force no longer existed the expansive action of heat should be independent of chemical composition. Hence, when the Swedish physicist Rudberg announced, as the result of his own more accurate experiments, that the coefficient of expansion found by Gay-Lussac was considerably too high, the statement was at first received with hesitation.

Rudberg first called in question the correctness of the principle that the coefficient of expansion of all gases is exactly equal to that of air, and he not only showed that the coefficient

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of the expansion of atmospheric air previously determined was inexact, but that other gases, though *nearly* equal in their rates of expansion to each other and to atmospheric air, were not precisely so. From the results obtained by Gay-Lussac, and the law of Mariotte (see HYDROSTATICS, page 155), it follows that, in a perfect gas, volume, pressure, and temperature would be related to each other in the manner expressed by the equation

$$pv = J(a + t), \quad . \quad . \quad . \quad . \quad . \quad (a),$$

where v is the volume of a given weight of the gas at the temperature t and under the pressure p , and J and a are constants. Hence, if v' were the volume of the same weight of the same gas corresponding to any other pressure, p' , and temperature, t' , we should have

$$\frac{pv}{p'v'} = \frac{a+t}{a+t'} \quad . \quad . \quad . \quad . \quad . \quad (b).$$

No absolutely perfect gas, however, is known in nature; so that, according to the best experiments, the values of a , which correspond to different values of p , v , and t , are not quite constant, but vary slightly, not only with variations of these factors, but also according to the nature of the gas. The properties of air, however, and the other non-condensable gases, accord so nearly with the above formulæ that, except in cases where extreme accuracy is required, the accord may be considered perfect.

If in the above equation (b) we make $p = p'$, we get

$$\frac{1}{a} = \frac{v - v'}{v't + vt'} \quad . \quad . \quad . \quad . \quad . \quad (c),$$

which means, that $\frac{1}{a}$ is the coefficient of expansion of the gas under constant pressure, or the amount by which that quantity of gas which occupies a unit of volume at 0° expands, under constant pressure, when its temperature is raised 1 degree. Similarly, by making $v = v'$, we have

$$\frac{1}{a} = \frac{p - p'}{p't + pt'},$$

or $\frac{1}{a}$ is the coefficient of expansion of the gas under constant volume, or, more correctly (since when $v = v'$ no actual expansion can take place), $\frac{1}{a}$ is the coefficient of increase of elasticity under a constant volume, for a rise of temperature of one degree of a gas whose elasticity at 0° C. is unity, for a perfect

gas these two values of $\frac{1}{a}$ would obviously be equal. Rudberg determined the value of the coefficient of expansion of air ($\frac{1}{a}$) between 0° and 100° C by two series of experiments. In the first he determined the contraction undergone by a given quantity of air on cooling from 100° to 0° under a nearly constant pressure; in the second, the difference in the elastic force at 0° and 100° of a quantity of air kept at the same volume at the two temperatures. Making t and t' in equations (c) and (d) respectively = 100 and 0, the results of his experiments may be stated as follows:—The mean of twelve experiments by the first method gave for the coefficient of expansion under constant pressure—

$$\frac{1}{a} = \frac{v - v'}{100v} = 0.003648 = \frac{1}{274}.$$

The mean of ten experiments by the second method gave for the coefficient of expansion at constant volume—

$$\frac{1}{a} = \frac{p - p'}{100p'} = 0.003646 = \frac{1}{274},$$

a result identical with the preceding.

84. Regnault's experiments.—More recently the expansion of air and other gases has been again made the subject of elaborate experiments by Regnault, who made five series of experiments by methods more or less distinct. His first method was the same as the first method employed by Rudberg. It consisted in heating a cylindrical glass vessel of known capacity, about 2.5 or 3 centimetres wide, and about 11 centimetres long, filled with dry air, to 100° ; sealing it hermetically at that temperature; then cooling it to 0° , and observing the quantity of mercury which entered on breaking off the point of the instrument under the surface of that metal. The apparatus employed and the method of experimenting were, in fact, exactly the same as in determining a temperature by means of an air thermometer quite similar to the weight-thermometer already described (Art. 47), for it is obvious that the same experiment which, the coefficient of expansion of air being known, serves to determine the temperature at which the air thermometer is sealed, would, if this temperature were known, serve for the determination of the coefficient of expansion.

The second set of determinations was made by a method only slightly different from the first, the only essential difference in the apparatus being that the tube connected with the air

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reservoir was about 40 centimetres (16 inches) long, and that a portion of it, about two inches long and separated from the air reservoir by about four inches, was wide enough to produce only a very slight capillary depression in a column of mercury. The effect of this modification of the apparatus was that when, after being heated to 100° and sealed at that temperature, the instrument was placed with the tube pointing vertically downwards and with the point dipping into mercury, the mercury rose only

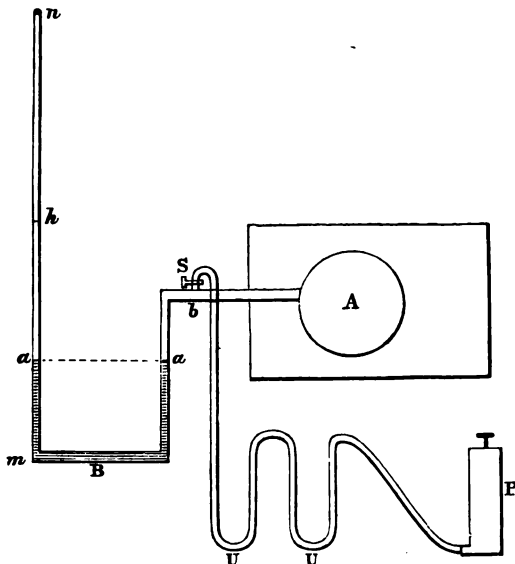


Fig. 35.

as far as the wide part of the tube on breaking off the point, and did not reach the reservoir at all. Hence the space occupied by the air at zero differed from that which it had occupied at 100° only by the capacity of that portion of the tube which became filled with mercury on opening the point; and since the diameter of the tube was, with the exception of the wider portion already mentioned, very small, this capacity bore a small proportion to the total capacity of the instrument. The experiment consisted therefore essentially in a determination of the difference of the elastic force of the air at the two temperatures. In the third and fourth sets of experiments, the air-reservoir was made to communicate with a manometer, whereby the pressure

upon the enclosed air could be varied at will and accurately measured. The pressures were so regulated that the air was caused to occupy accurately the same volume at 0° and 100° , and the differences of pressure required were determined. The apparatus for the third series of experiments was copied, with some improvements of detail, from that employed by Rudberg in his second series. The apparatus for the fourth series was the same in principle, but its construction was such that the pressure upon the air could be determined with still greater accuracy than was possible with the preceding apparatus.

The general principles on which the apparatus is constructed and employed, will appear from *fig. 35*. Δ is a glass balloon, of which the volume v at 0° has been measured. It is joined to the bent tube B , which contains mercury up to the level a in both branches. The capacity, v , of the portion of the tube ab is also ascertained. s is a stopcock with three channels, leading respectively to Δ , B , and through a series of drying tubes, U , U , filled with chloride of calcium, to the pump, P , which may be used either for exhausting or compressing the air in Δ .

At starting the balloon Δ is filled with dry air at 0° , and the temperature t of the air is noted. The volume of air in ab reduced to 0° is $= \frac{v(1+kt)}{1+at}$, k being the coefficient of expansion of glass, and a that of air. The total volume of air up to the mercury in the tube is thus at 0°

$$v + v \frac{(1+kt)}{1+at}$$

at the pressure of the atmosphere at the time, H , which is noted. The balloon is now raised to a temperature T , and the temperature and pressure of the air, t' and H' , are again observed. The volume v of glass balloon is now $v(1+kT)$ and the volume of air which it contains, reduced to 0° , is $v \frac{(1+kT)}{1+aT}$. Similarly the

volume of air contained in ab , reduced to 0° , is $v \frac{(1+kt')}{1+at'}$. Mer-

cury is now added in the open branch mn , so as to cause it to rise again to a , and the height of the column in the left branch of the tube above a , h is observed; let it be denoted by h . The air in the balloon now occupies the same volume as originally, when the temperature was t , and the pressure was H , but it is under a higher pressure, viz. $H' + h$, and at a different temperature; and as according to the law of Boyle and Mariotte the product

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of the volume of a gas into the pressure under which it exists is constant, we have

$$\left(v + v \frac{(1+kt)}{1+at}\right) H = \left[v \frac{(1+kt)}{1+at} + v \frac{(1+kt')}{1+at'} \right] (H' + h)$$

from which α may be calculated.

In the fifth set of experiments, the pressure upon the air remained constant, and the alteration of volume was determined by weighing the quantity of mercury which filled the space into which it expanded.

The mean results of numerous experiments made by each of these processes were as follows :—If p_0 and v_0 represent respectively the pressure and volume of the air at 0° , and p_1 and v_1 its pressure and volume at 100° , the value of $\frac{p_1 v_1}{p_0 v_0}$ was—

By the first series	1'36623
„ second series	1'36633
„ third series	1'36679
„ fourth series	1'36650
„ fifth series	1'36706

In the second, third, and fourth series, the expansion was calculated from the change of elastic force undergone by the same volume of air when its temperature changed between 0° and 100° ; in the experiments made by the first method, both pressure and volume changed considerably, so that they gave a mixed result. From the consideration of all the experiments by the first four methods, Regnault adopts for the coefficient of expansion of air, under constant volume, for one degree Centigrade between 0° and 100° , the number

$$0\cdot003665 = \frac{1}{272\cdot9} = \frac{1}{273} \text{ nearly.}$$

This result agrees precisely with that obtained by Magnus.

For the coefficient of expansion of air under constant pressure Regnault adopts the number

$$0\cdot00367$$

given by the experiments of the fifth series.

Similar experiments extended to other gases gave the mean results recorded in the following table, in which are also included the results obtained by Magnus :—

Table of Expansion of Gases between 0° and 100° at ordinary Pressures.

Name of Gas	At constant volume	Volume at 0° = 1'0000	At constant pressure
	Regnault	Magnus	Regnault
Hydrogen	1'3667	1'3657	1'3661
Air	1'3665	1'3665	1'3670
Nitrogen	1'3668	—	—
Carbonic Oxide . .	1'3667	—	1'3669
Carbonic Anhydride .	1'3688	1'3691	1'3710
Nitrous Oxide . .	1'3676	—	1'3719
Sulphurous Anhydride .	1'3845	1'3856	1'3903
Cyanogen	1'3829	—	1'3777

85. Expansion of gases at pressures different from that of the atmosphere.—The foregoing results are all deduced from experiments in which the gases operated upon were subject to pressures differing but little from the ordinary pressure of the atmosphere. In another investigation Regnault determined the coefficients of expansion of air and some other gases at pressures considerably different from that of the atmosphere. The following table gives the mean results :

*Table of Expansion of Gases between 0° and 100° at Various Pressures.**Air.*

Constant Volume		Constant Pressure	
Density (Density of air at 0° and 760 mm. pres- sure = 1)	—	Pressure in millimetres	—
0'1444	1'36482	760	1'36706
0'4937	1'36572	2525	1'36944
1'0000	1'36650	2620	1'36964
2'2084	1'36760		
2'8213	1'36894		
4'8100	1'37091		

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Carbonic Anhydride.

Constant Volume		Constant Pressure	
Density (Density of carbonic anhydride at 0° and 760 mm. pressure = 1)	—	Pressure in millimetres	—
1'0000	1'36856	760	1'37099
1'1879	1'36943	2520	1'38455
2'2976	1'37523		
4'7318	1'38598		

Hydrogen.

Sulphurous Anhydride.

Constant Pressure		Constant Pressure	
Pressure in milli- metres	—	Pressure in milli- metres	—
760	1'36613	760	1'3903
2545	1'36616	985	1'3984

Thus, under $3\frac{1}{2}$ atmospheres the dilatation of hydrogen remains unvaried, but the dilatation of air increases from 0'367 to 0'369, and that of carbonic acid from 0'371 to 0'385, while the dilatation of sulphurous acid, under a pressure of only one atmosphere, increases from 0'390 to 0'398.

Thus it appears that although it be certain that the gases are subject to a small difference in their rates of dilatation, and also that the rate of dilatation of the same gas is not absolutely the same at different pressures, yet the inequality and variations are such as may be disregarded for all practical purposes ; and it may be assumed that all gases and all vapours dilate uniformly, and in the same degree as atmospheric air.

86. **Application of results.**—The increment of volume of any gas between 0° and 100° may thus be taken as the $\frac{3663}{10000}$ th part of its volume at 0°, or more than one-third of the latter. It follows that ten cubic inches of atmospheric air at 0° will, if raised to the temperature of 100°, become, by dilatation, nearly

13 $\frac{7}{10}$ cubic inches ; and, for every additional 100° of temperature which it receives it will undergo a like increase of volume.

To find the increment of volume corresponding to one degree of temperature on the Centigrade scale, we have only to divide the fraction $\frac{3665}{10000}$ by 100, which gives $\frac{3665}{1000000}$, or $\frac{1}{273}$; while by dividing the same fraction by 180 we find the increment for one degree on *Fahrenheit's scale* to be $\frac{1}{461}$ of the volume at 0°.

The following formulæ will serve to calculate the change of volume which atmospheric air, or any other gas which dilates equally with it, undergoes for any proposed change of temperature.

Let v express a volume of air at 0°.

Let v express its volume when raised to a temperature which exceeds 0° by a number of degrees expressed by τ .

The increment of volume, therefore, corresponding to the increment of temperature expressed by τ will be $v - v$; and since the increment of volume corresponding to 1° is $\frac{v}{273}$, the

increment corresponding to τ degrees will be $\frac{v}{273} \times \tau$. We shall therefore have

$$v - v = \frac{v}{273} \times \tau ;$$

and consequently

$$v = \left(1 + \frac{\tau}{273}\right) \times v.$$

In this case the gas has been supposed to be submitted to an increase of temperature. If it be reduced to a lower temperature, it will suffer a decrement of volume, expressed by $v - v$; and if τ express the number of degrees below 0° to which it is reduced, the decrement of volume for 1° being $\frac{v}{273}$, the de-

crement for τ degrees will be as before, $\frac{v}{273} \times \tau$, and we shall have

$$v - v = \frac{v}{273} \times \tau,$$

from which we find,

$$v = \left(1 - \frac{\tau}{273}\right) \times v.$$

If, therefore, the volume of a gas at 0° be known, its volume at any other temperature above or below 0° may be calculated.

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By substituting the number 491 for 273 in any of the preceding formulæ the volumes of gases may be calculated for temperatures observed by Fahrenheit's thermometer. They may obviously be found by the following

RULE.

Divide the difference between the number of degrees in the temperature and 32° by 491. Add the quotient to 1 if the temperature be above 32°, and subtract it from 1 if it be below 32°. Multiply the volume of the gas at 32° by the resulting number, and the product will be the volume of the gas at the proposed temperature.

In the columns v of the following table are expressed in cubic inches the volumes which a thousand cubic inches of air at 32° will have at the temperatures expressed in the columns t, being supposed to be maintained under the same pressure.

T.	V.	T.	V.	T.	V.	T.	V.	T.	V.
-50	832.7	-10	914.3	30	995.9	70	1077.6	110	1159.2
-49	834.7	-9	916.3	31	998.0	71	1079.6	111	1161.2
-48	836.7	-8	918.4	32	1000.0	72	1081.6	112	1163.3
-47	838.8	-7	920.4	33	1002.0	73	1083.7	113	1165.3
-46	840.8	-6	922.5	34	1004.1	74	1085.7	114	1167.3
-45	842.8	-5	924.5	35	1006.1	75	1087.8	115	1169.4
-44	844.9	-4	926.5	36	1008.2	76	1089.8	116	1171.4
-43	846.9	-3	928.6	37	1010.2	77	1091.8	117	1173.5
-42	849.0	-2	930.6	38	1012.2	78	1093.9	118	1175.5
-41	851.0	-1	932.7	39	1014.3	79	1095.9	119	1177.6
-40	853.1	0	934.7	40	1016.3	80	1098.0	120	1179.6
-39	855.1	1	936.7	41	1018.4	81	1100.0	121	1181.6
-38	857.1	2	938.8	42	1020.4	82	1102.0	122	1183.7
-37	859.2	3	940.8	43	1022.4	83	1104.1	123	1185.7
-36	861.2	4	942.9	44	1024.5	84	1106.1	124	1187.8
-35	863.3	5	944.9	45	1026.5	85	1108.2	125	1189.8
-34	865.3	6	947.0	46	1028.6	86	1110.2	126	1191.8
-33	867.3	7	949.0	47	1030.6	87	1112.2	127	1193.9
-32	869.4	8	951.0	48	1032.7	88	1114.3	128	1195.9
-31	871.4	9	953.1	49	1034.7	89	1116.3	129	1198.0
-30	873.5	10	955.1	50	1036.7	90	1118.4	130	1200.0
-29	875.5	11	957.1	51	1038.8	91	1120.4	131	1202.0
-28	877.6	12	959.2	52	1040.8	92	1122.4	132	1204.1
-27	879.6	13	961.2	53	1042.9	93	1124.5	133	1206.1
-26	881.6	14	963.3	54	1044.9	94	1126.5	134	1208.2
-25	883.7	15	965.3	55	1046.9	95	1128.6	135	1210.2
-24	885.7	16	967.3	56	1049.0	96	1130.6	136	1212.2
-23	887.8	17	969.4	57	1051.0	97	1132.7	137	1214.3
-22	889.8	18	971.4	58	1053.1	98	1134.7	138	1216.3
-21	891.8	19	973.5	59	1055.1	99	1136.7	139	1218.4
-20	893.9	20	975.5	60	1057.1	100	1138.8	140	1220.4
-19	895.9	21	977.6	61	1059.2	101	1140.8	141	1222.4
-18	898.0	22	979.6	62	1061.2	102	1142.9	142	1224.5
-17	900.0	23	981.6	63	1063.3	103	1144.9	143	1226.5
-16	902.0	24	983.7	64	1065.3	104	1147.0	144	1228.6
-15	904.1	25	985.7	65	1067.3	105	1149.0	145	1230.6
-14	906.1	26	987.8	66	1069.4	106	1151.0	146	1232.7
-13	908.2	27	989.8	67	1071.4	107	1153.1	147	1234.7
-12	910.2	28	991.8	68	1073.5	108	1155.1	148	1236.7
-11	912.2	29	993.9	69	1075.5	109	1157.1	149	1238.8

T.	V.	T.	V.	T.	V.	T.	V.	T.	V.
150	1240.8	168	1277.5	186	1314.3	204	1351.0	220	1383.7
151	1242.9	169	1279.6	187	1316.3	205	1353.1	230	1404.1
152	1244.9	170	1281.6	188	1318.4	206	1355.1	240	1424.5
153	1246.9	171	1283.7	189	1320.4	207	1357.1	250	1444.9
154	1249.0	172	1285.7	190	1322.4	208	1359.2	260	1465.3
155	1251.0	173	1287.8	191	1324.5	209	1361.2	270	1485.7
156	1253.0	174	1289.8	192	1326.5	210	1363.3	280	1506.1
157	1255.1	175	1291.8	193	1328.6	211	1365.3	290	1526.5
158	1257.1	176	1293.9	194	1330.6	212	1367.3	300	1546.9
159	1259.2	177	1295.9	195	1332.6	213	1369.4		
160	1261.2	178	1298.0	196	1334.7	214	1371.4	300	1546.9
161	1263.3	179	1300.0	197	1336.7	215	1373.5	400	1751.0
162	1265.3	180	1302.0	198	1338.8	216	1375.5	500	1955.1
163	1267.3	181	1304.1	199	1340.8	217	1377.5	600	2159.2
164	1269.4	182	1306.1	200	1342.9	218	1379.6	700	2363.3
165	1271.4	183	1308.2	201	1344.9	219	1381.6	800	2567.3
166	1273.5	184	1310.2	202	1346.9	220	1383.7	900	2771.4
167	1275.5	185	1312.2	203	1349.0			1000	2975.5

The figures in this table may easily be adapted to any other thermometric scale by means of the formulæ given in article 24, or with the help of the table on pages 17 and 18. Again, the volume 1,000 at 32° Fahrenheit may stand for 1,000 cubic centimetres, or 1'000 litre, and thus, by cutting off three decimals from any integer which gives the volume in cubic inches corresponding to any temperature, the same volume in litres may at once be found by inspection.

87. Increase of pressure due to increase of temperature.—If air or gas be included within any limits which prevent its expansion by increase of temperature, its elastic force or pressure will be increased in the same proportion as its volume would be increased if it were not thus confined. Thus if a certain quantity of air confined under a given pressure receive such an increase of temperature as would cause it to expand into double its volume, and if, after having so expanded, it be subject to such an increased pressure as will reduce it to its primitive volume, it will acquire double its primitive pressure. This follows from the principle already established, that the pressure of air and gas is inversely as the volume into which they are compressed.

It will be convenient, however, to establish general formulæ by which the relation between the volume and temperature of the same gases under different pressures may be expressed, so that the volume at any given temperature and pressure being given, the volume at any other temperature and pressure may be obtained.

It has been already shown that at the same temperature the volume will be inversely as the pressure; so that if v and v'

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be two volumes at the same temperature and under the pressures P and P' , we shall have

$$V : V' :: P' : P ;$$

and therefore

$$V' = V \times \frac{P}{P'}$$

Hence it follows, that if the same quantity of air or gas be simultaneously submitted to changes of temperature and pressure, the relation between its volumes, pressures, and temperatures will be expressed by the general formula

$$\frac{V}{V'} = \frac{273 + T}{273 + T'} \times \frac{P'}{P} ;$$

where T and T' express the number of degrees above or below 0° at which the temperature stands, $+$ being used when *above* and $-$ when *below* 0° , and the pressures being expressed in the usual manner by P and P' .

By this formula, the volume of a gas at any proposed temperature and pressure may be found, if its volume at any other temperature and pressure be given.

It follows from these considerations that, in stating the *absolute* density of a gas, it is very important to specify the temperature and pressure at which we suppose it to be taken ; on the other hand, in stating the *relative* density or specific gravity of a gas, as compared with any other gas which is taken as a standard substance, it must be understood that the gas is at the same temperature and pressure as the standard gas with which it is compared, and it is further necessary to specify the temperature and pressure at which the comparison has actually been made, since the laws of Boyle and Gay-Lussac are only approximately true.

The methods of calculating specific gravities of gases from actual experiments are described in detail in the PROBLEMS at the end of this work.

88. Practical applications of the expansion of gases.—The expansion and contraction of air explain a multitude of phenomena which present themselves in the natural world, in domestic economy, and in the arts.

In the ventilation and warming of buildings, the entire process, whatever expedients may be adopted, is dependent upon this principle. When a fire is lighted in an open stove to warm a room, the smoke and the gaseous products of combustion, ascending the chimney, soon fill the flue with a column of air so

expanded by heat as to be lighter, bulk for bulk, than a similar column of atmospheric air. Such a column, therefore, will have a buoyancy proportional to its relative lightness. This upward tendency is what constitutes the draught of the chimney; and this draught will accordingly be strong and effective in just the same proportion as the column of air in the chimney is kept warm. When the fire is first lighted, the chimney being filled with cold air, there is no draught, and, consequently, the flame and smoke often issue into the room. According as the column of air in the chimney becomes gradually warm, the draught is produced and increased. The draught is sometimes stimulated by holding burning fuel for some time in the flue, so as to warm the lower strata of air in it.

But the most effectual method of stimulating the draught when the fire is lighted is by what is called a *blower*, which is a sheet of iron that stops up the space above the grate bars, and prevents any air from entering the chimney except that which passes through the fuel and produces the combustion. This soon causes the column of air in the chimney to become heated, and a draught of considerable force is speedily produced through the fire.

From the principles explained in the volume on HYDROSTATICS, articles 145 and 155, we may derive a numerical expression for the velocity of the upward current in chimneys. Suppose the chimney to be cylindrical and its height to be h . Let the temperature of air within the chimney be supposed to be uniform and equal to t' degrees, while that of the external air is t . Then from Torricelli's theorem, as stated in the above articles, the square of the linear velocity of efflux is given by the formulæ

$$v^2 = 2 g h,$$

where h is the length of the vertical column of fluid which produces efflux by its pressure. In the present case this column is the difference between H , which is the height of air within the chimney, and the height which a column of the external air of original height H would have if expanded upwards by raising its temperature from t to t' . This latter height is

$$\frac{H (1 + a t')}{1 + a t},$$

where a is the coefficient of expansion of air, = .003665. The height of the pressing column is therefore

$$\frac{H (1 + a t')}{1 + a t} - H = \frac{H a (t' - t)}{1 + a t}.$$

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Hence the velocity of the current up the chimney is given by

$$v = \frac{2 g H a (t' - t)}{1 + a t}.$$

In consequence of our neglecting to take account of friction and eddies, this result is in excess of the truth, but it is sufficiently near it to explain the principal circumstances on which the strength of draught depends, viz., that the draught increases with the height H of the chimney, and also with the difference $t' - t$ between the internal and external temperatures.

An open chimney differs from a close stove, inasmuch as the former serves the double purpose of warming and ventilating the room, whereas the latter only warms, and can scarcely be said to ventilate. In a close stove, no air passes through the room to the flue of the chimney, except that which passes through the fuel, and that is necessarily limited in quantity by the rate of combustion maintained in the stove. In an open fire-place, on the other hand, two independent currents of air pass into the flue: one is that which passes through the fuel and maintains the combustion, and the other, which is far more considerable in quantity, is that which passes through the opening of the fire-place above the grate.

The temperature of the column in the flue is due entirely to the former, and the activity of the combustion will be determined by the relative magnitudes of the grate and the space above it; these two magnitudes representing the proportion in which the open stove serves the two purposes of warming and ventilation, the grate representing the function of warming, and the space above it the function of ventilating. Even when there is no fire lighted in the grate, the column of air in the chimney is in general at a higher temperature than the external air, and a current will therefore in such case be established up the chimney, so that the fire-place will still serve, even in the absence of fire, the purposes of ventilation. In very warm weather, however, when the external air is at a higher temperature than the air within the building, the effects are reversed; and the air in the chimney being cooled, and therefore heavier than the external air, a downward current is established, which produces in the room the odour of soot. To prevent this, a trap or valve is usually provided in it, which can be closed at pleasure so as to intercept the current. It should be observed, however, that this trap should only be closed when a downward current is established; since, at other times, even in the absence of fire, the ventilation of the apartment is maintained.

In all apparatus adapted to warm buildings, the fact that warm air is more expanded, and therefore lighter, bulk for bulk, than cool air, requires to be attended to. It is usual to admit the warm air through apertures placed in the lower parts of a room, because it will ascend by its buoyancy and mix with the colder air, whereas if it were admitted by apertures near the ceiling it would form strata in the upper part of the room, and would escape at any apertures which might be found there. But if there be means of escape only in the lower part of the room, then the strata of warm air let in above will gradually press down upon the cool air below and force it out through the chimney, doors, windows, or other apertures.

In general, the air contained in an apartment collects in strata arranged according to its temperature, the hotter air collecting near the ceiling, and the strata decreasing in temperature downwards. Thermometers placed at different heights between the floor and the ceiling would accordingly show different temperatures. The difference of these temperatures is sometimes so considerable that flies will continue to live in one stratum which would perish in another.

If the door of an apartment be open it will be found that two currents are established through it, the lower current flowing inwards and the upper outwards. If a candle be held in the doorway near the floor, it will be found that the flame will be blown inwards : but if it be raised nearly to the top of the doorway, the flame will be blown outwards. The warm air in this case flows out at the top, while the cold air flows in at the bottom.

89. Warming buildings by heated air.—Although open fire-places placed in dwelling-rooms are agreeable to the eye, and healthful so far as they generally ensure an efficient ventilation, they are extremely costly, an enormous proportion of the heat developed by the fuel passing up the chimney without in any way contributing to the warmth of the room. In public buildings and other places, where all the apartments can be warmed by a common apparatus, the object is attained with much greater economy. Two methods are practised ; one by currents of heated air, and the other by currents of heated water.

The method of warming buildings by currents of heated air will be easily understood by reference to *fig. 36*, where *F* is a furnace constructed in the basement of the building, over which there is a metal pipe carried, following a winding course. The flame and heated air, passing round this pipe, raise the air in it to a high temperature. A current of cold air enters at the end *B*

ascending through a room, it will be easy to show that when it is strongly heated ascending currents of air are established around it. Thus, if light be directed towards it, so as to make it project a shadow, the agitation of the ascending air around it will also produce a visible undulating shadow along the borders of the shadow of the stove pipe.

The existence of the current may be rendered still more manifest by attaching to the side of the stove pipe a wire, on which

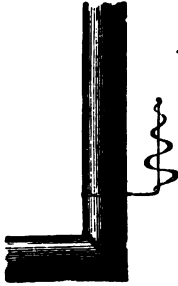


Fig. 37.

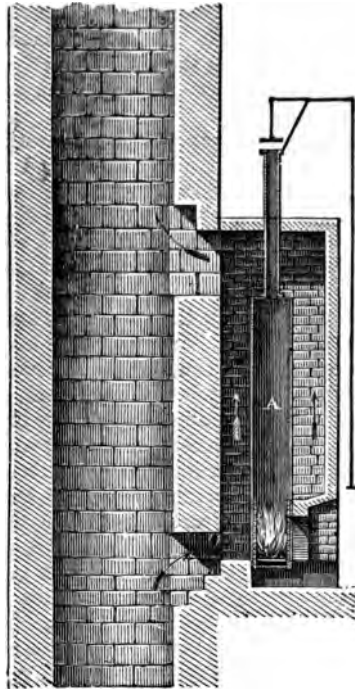


Fig. 38.

a piece of paper cut in the shape of a spiral may be suspended, as shown in *fig. 37*. The upward current will immediately put the paper in motion, and make it revolve rapidly round the wire.

Upon this principle a current is established in the shaft of a mine by erecting a stove in a short shaft built in juxtaposition

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with it. Such an arrangement is shown in vertical section in *fig. 38*. The shaft of the mine is represented on the left of the figure, and the ventilating shaft communicating with it at top and bottom on the right. At the base of the ventilating shaft a stove is established, the pipe of which, *A*, passing up the middle of the shaft, issues from the top, where it is provided with a damper to regulate the draught. The stove is built into the base of the shaft, so that the fire has no communication with the air in it, and the pipe passes through the top of the shaft, so as to be air-tight. Upward currents are established round the pipe, *A*, upon the principle already explained. These currents have the effect of drawing the air through the lower, and discharging it through the upper opening, and thus establishing an upward current in the shaft.

91. **Argand lamp.**—The combustion which produces the flame of an argand lamp is maintained upon the same principle as that by which the combustion is maintained in a common fire-place. The wick, which is cylindrical, surrounds a brass tube which communicates at its lower end with the external air. A glass chimney surrounds the wick and the flame. The air, ascending through the glass tube, passes the flame and is heated by it, and then ascends in the glass chimney within which it is confined. This glass chimney is, therefore, filled with a column of heated air, which has a buoyancy proportional to its expansion, and ascends with a proportionate force, fresh air being supplied to the wick continually through the brass tube already mentioned. But as the column of air ascending through this brass tube would only touch the flame on its external surface, the internal parts of the column would not be so strongly heated. To increase the heat imparted to the air, therefore, a metal wire is placed in the centre of the brass tube, which supports a button a little less in diameter than the wick at the level of the flame. When the column of air which ascends in the tube encounters this button, the central parts of the column are intercepted, and can only ascend by passing round the edge of the button, and therefore in contact with the flame. By this expedient all the air which ascends through the brass tube is made to pass in close contact with the flame before it can enter the glass chimney above the flame, and thus the intensity of the force of the draught is increased and the combustion is augmented.

92. **Experiments.**—The expansion of air by heat and its contraction by cold may be made manifest by a variety of simple and easily executed experiments. If a common drinking-glass be inverted and held over the flame of a lamp or candle for some

time, it will be filled with air heated by the flame ; if it be then suddenly plunged with its mouth downwards in water, the water will be found to rise in the glass to a height above the level of the water outside the glass. The cause of this is, that the air which fills the glass, having been previously rarefied by heat and afterwards cooled, when removed from the lamp is contracted so as to fill a less space than the capacity of the glass which it filled when heated previous to immersion.

This experiment may be rendered still more striking by using a glass bulb blown at the end of a tube, like a thermometric tube, instead of a glass. Let such a bulb be held for some minutes over the flame of a spirit-lamp. The air which fills it will become highly expanded and rarefied by the heat. Let the open end of the tube be then plunged in water, the bulb being presented upwards. After some time, when the tube has cooled and the air within it contracted, the water will rise in the tube, and will nearly fill the bulb, the portion of the bulb not filled being the space within which the air previously heated had been contracted by cooling.

93. **Absolute temperature. Absolute zero.**—If in a thermometer air or any permanent gas be made the thermometric substance, then equal differences in the volume occupied by a given mass of air at constant pressure will correspond to equal differences of temperature ; and it has been shown that this difference amounts to $\frac{1}{273}$ of the volume at 0° C. for each degree Centigrade, or to $\frac{1}{459}$ of the volume at 32° F. for each degree Fahrenheit. Hence, if we suppose a given mass of air, at 0° C., to be cooled to -273° C., it will be reduced to a mathematical point, or, in other words, its elastic force must at that temperature completely vanish. The temperature of -273° C., or -459° F., has for these reasons been called the *absolute zero* of temperature, and temperatures reckoned from it are called *absolute temperatures*. By employing this term, the statement of the relations between the volume, pressure, and temperature of a given mass of air or gas may be simplified thus, assuming the correctness of the laws of Boyle (or Mariotte) and of Gay-Lussac :—(I.) *When the pressure is constant, the volume of a gas varies directly as the absolute temperature.* (II.) *When the volume is constant, the pressure varies directly as the absolute temperature.* (III.) *If V, P, T, denote volume, pressure, and absolute temperature, then the value of the expression $\frac{VP}{T}$ remains, for all variations, constant.*

CHAPTER VI.

CALORIMETRY.

94. **Object of calorimetry.**—The *quantitative determination of heat* forms a special department called *Calorimetry*, and the instruments by which quantities of heat are measured are called *Calorimeters*.

If the same quantity of heat always produced the same or equal thermometric changes, every thermometer would be a calorimeter, and *calorimetry* would not form a part of this subject distinct from *thermometry*. But not only do equal quantities of heat produce unequal thermometric changes on different bodies, but even on the same body at different points of the scale, and in some cases no thermometric change whatever.

That different bodies, although at the same temperature, differ very widely from one another as respects the *quantity of heat* in each of them, may be easily demonstrated by the following experiment. A number of balls, of equal weight but of different materials, are heated to the same temperature, suppose 200° , and placed upon a wax disc. Each of the balls gives up part of its heat to the wax, causing it to melt, and thus making a hole through which the ball finally drops. The balls containing the greatest quantity of heat drop through first; thus an iron ball melts its way through the wax before one of copper, a copper ball before one of tin, &c., while balls of lead or bismuth are much slower in their action, and never get through at all if the disc be moderately thick. Now although the metal balls were at the same temperature, and have the same weight, yet one does not melt as much wax as the other, in other words, the lead ball, for example, does not part with as much heat as the iron ball, whilst both are cooling from 200° to the temperature of the air. It follows that different bodies at the same temperature contain different quantities of heat; they part with different quantities when cooled through the same number of degrees of temperature, and require different quantities when their temperature is raised by the same number of degrees.

95. **Thermal unit.**—To reduce heat to arithmetical expression it is necessary that some suitable thermal measure be adopted, and a thermal unit selected. It may be assumed as self-evident that to produce the same thermal effect on the same

quantity of the same body under like circumstances will always require the same quantity of heat. Thus, it is apparent that to raise a pound of pure water from 0° to 1° , or to liquefy a pound of ice, or to convert a pound of water into vapour under a given pressure, will always require the same quantity of heat, from whatever source such heat may proceed. Water has been selected as the standard of thermal measure, for reasons nearly the same as those which have determined its selection as the standard of specific gravity, and also because water, as will be seen further on, possesses a very high capacity for heat, higher than almost all other substances. We may, therefore, take as the thermal unit the quantity of heat which is necessary to raise a pound of pure water from 0° to 1° . But several different units of heat are employed, all having reference to pure water as the standard substance. Our unit may be called the *Pound-Degree* (Fahrenheit or Centigrade), meaning the heat required to raise a pound avoirdupois of water 1° F. or 1° C., and it is obvious that either one or the other of these thermometric scales must be adopted. In speaking therefore of a Pound-Degree, we shall henceforth mean the heat required to raise a pound of water from 0° to 1° of the Centigrade scale. Again the *Kilogramme-Degree* is the heat required to raise a kilogramme of water from 0° to 1° Centigrade; this unit has sometimes been called the *Calorie*. Similarly the *Gramme-Degree* is the quantity of heat required to raise a gramme of water 1° Centigrade.

96. **Definition of specific heat.**—The quantity of heat which is necessary to raise a pound of any other body from 0° to 1° , is in general different from that which would produce the same effect on water, and in general also different for different species of bodies. These quantities of heat, expressed relatively to the quantity of heat required to raise the temperature of an equal weight of water from 0° to 1° C. are called the *specific heats* of the various substances.

The specific heat of a body is said to be uniform throughout any extent of the thermometric scale when it requires the same quantity of heat to raise the temperature one degree through such extent of the scale. If H express the quantity of heat necessary to raise w lbs. of a body from the temperature expressed by T' to the temperature expressed by T , the specific heat being expressed by s and being uniform, we shall therefore have

$$H = s \times (T - T') \times w ;$$

that is to say, the quantity of heat is found by multiplying together the numbers expressing the specific heat, the elevation

H

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of temperature, and the weight in lbs. When the quantity of heat necessary to raise a body one degree is different in different parts of the scale, the specific heat is said to be *variable*; and when it does so vary, it is in general found to increase with the temperature.

97. **Calorimetric methods.**—Three methods have been practised for the solution of calorimetric problems: 1st, by measuring the heat by the quantity of ice it liquefies; 2ndly, by calculating it by means of mixing or bringing into close juxtaposition different bodies at different temperatures, so that their temperatures shall be equalised; and 3rdly, by observing the rate at which different heated bodies cool.

The calorimeter of *Lavoisier* and *Laplace* is based upon the first of these principles.

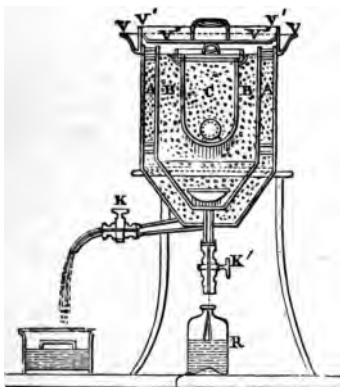


Fig. 39.

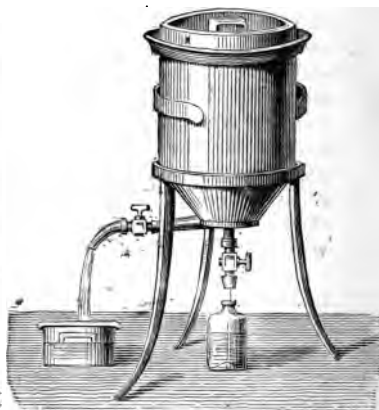


Fig. 40.

This apparatus is represented in *fig. 39* in section, and in *fig. 40* in perspective. Two similar metallic vessels *v* and *v'* are constructed, one a little smaller than the other, so that, when applied one within the other, a small space *a* may be left between them. From the bottom of the external vessel *v* a discharge pipe, with a stop-cock *K*, proceeds. From the bottom of the inner vessel a similar pipe proceeds, which passes water-tight through the bottom of the vessel *v*, and is also furnished with a stop-cock *K'*.

This pipe *K'* leads into a vessel *R*. The external vessel *v* has a close cover, by which all communication with the external air is cut off, and the inner vessel *v'* is likewise furnished with

a small cover, by which all communication with the space Λ is intercepted. The space Λ between the two vessels is filled with pounded ice; and if the apparatus be placed in an atmosphere above 0° , this ice will be gradually liquefied, and the water produced by it will flow off through the cock x , when the stop-cock is open, and will be received in the vessel shown in the figure. The space Λ being kept continually supplied with ice, it is evident that the interior vessel v' will be maintained constantly at the temperature of 0° , and the air included in it, and any objects placed in it, will be necessarily reduced to that temperature.

A third vessel v'' is now placed within the second v' , and the space B between the second and third is filled with pounded ice, in the same manner as the space Λ . But it is evident that this ice cannot be affected by the temperature of the external air, since it is surrounded with the melting ice included in the space Λ , which is continually at 0° .

If any object at a temperature above 0° be placed at c , within the vessel v'' , this object will gradually fall in its temperature by imparting its heat to the ice in the space B ; and it will continue to impart heat, and its temperature will continue to fall, until it arrives at the temperature of 0° , when it will cease to liquefy the ice around it. The water proceeding from the liquefaction of the ice in the space B is discharged through the pipe κ' , the stop-cock being opened, and is received in the vessel x . The quantity of water thus received in x will therefore be proportional to the heat imparted by the body contained in the vessel v'' to the ice in the space B .

If this apparatus be applied to solid bodies, it will be sufficient to introduce the body under experiment directly into the interior of the vessel v'' ; but if it be applied to liquids, it will be necessary that the liquid under experiment should be contained in a vessel, which vessel is introduced into v'' . In this case the vessel containing the liquid should be reduced to the temperature of 0° before receiving the liquid, or, if not, the vessel should be raised to the temperature of the liquid, and introduced empty into the calorimeter, so as to ascertain the quantity of ice it would dissolve empty in falling from the temperature of the liquid to 0° . When the vessel is introduced, filled with the liquid, the quantity of ice liquefied will be the sum of the quantities liquefied by the vessel and by the liquid which it contains. But the quantity liquefied by the vessel being previously ascertained and subtracted, the remainder will be the quantity dissolved by the liquid contained in the vessel.

If equal weights of the same substance, placed in the apparatus

at different temperatures, cause quantities of water to be deposited in \mathbf{R} which are proportional to the temperatures through which they fall, it will follow that within such limits the specific heat is uniform. And, if the quantity of water deposited in \mathbf{R} be divided by the number of degrees through which the temperature of the body placed in the calorimeter has fallen, the quantity of ice dissolved by the heat corresponding to one degree will be found. This, in fine, being divided by the weight of the body placed in the calorimeter expressed in pounds, the weight of ice dissolved by the heat which would raise 1 lb. of the body one degree will be determined.

To express this in algebraical symbols :—

Let w = the weight of the body placed in the calorimeter,

\mathbf{T} = its temperature,

w' = the weight of water deposited in \mathbf{R} while the body is reduced from \mathbf{T}° to 0° ,

x = weight of ice dissolved by the heat which would raise 1 lb. of the body one degree.

We shall then have,

$\frac{w'}{\mathbf{T}}$ = the weight of ice dissolved by the heat which would raise w one degree ;

and therefore,

$$x = \frac{w'}{w\mathbf{T}}$$

In applying this method of experimenting to water, it is found that between the freezing and boiling points its specific heat is sensibly uniform, and that the heat necessary to raise 1 lb. of water one degree is that which would melt the 80th part of a lb. of ice, so that in the case of water we have

$$x = \frac{1}{80}$$

For other bodies, let s be the specific heat of the body w , that of water being the unit. Hence we shall have by proportion :—

$$s : 1 :: \frac{w'}{w\mathbf{T}} : \frac{1}{80}$$

and consequently

$$s = \frac{80 \times w'}{w\mathbf{T}}$$

which gives the following rule :—

Multiply the weight of ice dissolved by 80 ; multiply the weight of the body which dissolves the ice by the number of degrees of temperature it loses ; and divide the former product by the latter. The quotient will be the specific heat of the body.

There are several important objections to the use of this apparatus, although the principle of the method is simple and the experiment consists essentially of only two operations, viz., the precise determination of the temperature of the body which is placed in the calorimeter, and the accurate weighing of the discharged water. But in consequence of the large quantity of heat required for melting an appreciable quantity of ice, the apparatus is only available for substances of which large masses are at the disposal of the experimenter. But it is absolutely necessary to fuse a considerable quantity of ice in each experiment, if the result is to be a trustworthy one. The reason is, that a certain weight of the melted water remains adhering to the ice in the calorimeter, so that the water which flows out does not exactly represent the weight of the melted ice ; but this deficiency will influence the result in a much less proportion the greater the absolute quantity of the melted ice.

Another source of error is, that the external space gives up heat to the calorimeter in spite of all precautions, and unless the external space is at 0° , some ice will be melted by radiation and conduction from without.

98. **Bunsen's ice-calorimeter.**—Ice experiences a considerable diminution of volume when it melts and passes into water. On this fact Bunsen has based a calorimeter, represented in *fig. 41*, which is particularly suitable for experimenting on substances of which only small quantities can be used. A is a small test tube fused in the wide tube B, and is intended to receive the substance of which the specific heat is to be determined. After being heated in a current of steam of known temperature, the body is dropped as quickly as possible

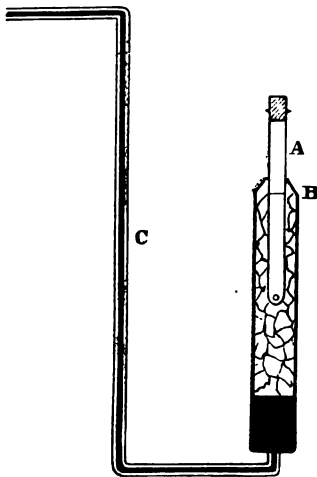


Fig. 41.

into the test tube A, which contains water at 0° . The tube is surrounded by the ice in B, the lower part of which contains mercury, and is connected with the capillary tube C, also containing mercury. The upper part of this tube is bent horizontally, and is carefully calibrated and graduated. As soon as the body is introduced into the test tube it imparts its heat to it while it sinks to zero, and in doing so melts a certain quantity of ice: the mercury in the capillary tube recedes, and the weight of the quantity of ice melted may be calculated from the observed diminution of volume. This, together with the weight and original temperature of the substance, furnish all data required for calculating the specific heat.

99. **Method of mixtures.**—When two bodies at different temperatures are mixed, or brought into juxtaposition in such a manner that that which has the higher temperature may transfer to that which has the lower temperature such a portion of its heat that the temperatures may be equalised, the relation between the specific heats may be determined, provided no chemical action nor any change of state be produced by the contact or mixture.

Let the weights of the two bodies be w and w' , their temperatures t and t' , and their specific heats s and s' ; and let t be their common temperature after the thermometric equilibrium has been established. It will therefore follow that the temperature lost by w will be $t - t'$, and the temperature gained by w' will be $t - t'$. But from what has been already explained, the quantity of heat lost by w will be expressed by $s \times w \times (t - t')$, and the quantity of heat gained by w' will be expressed by $s' \times w' \times (t - t')$. But since the quantity of heat lost by w is imparted to w' , these two quantities must be equal, and consequently we must have

$$w \times s \times (t - t') = w' \times s' \times (t - t') ;$$

and from this we infer that

$$s : s' :: w' \times (t - t') : w \times (t - t') ;$$

that is to say, the specific heats of the two bodies are in the inverse proportion of the products of their weights and the temperatures which they gain and lose.

This method of determining the relation between the specific heats is applicable either to two liquids or to a solid and a liquid, provided that when they are mixed or brought together no chemical action takes place between them, and provided the solid be not liquefied. But if such action ensue, it is generally attended with the development or absorption of sensible heat,

by which the common temperature would be rendered either higher or lower than that which would result from mere admixture.

If one of the bodies, w' , be water, we shall have $s' = 1$, and therefore

$$s = \frac{w' \times (t - T')}{w \times (T - t)};$$

from which follows the

RULE.

Let the weight of a heated body immersed in water be multiplied by the temperature it loses, and let the weight of the water be multiplied by the temperature it gains. The quotient obtained by dividing the latter product by the former will be the specific heat of the body.

The method of determining the specific heat of gaseous bodies by means of the water calorimeter of Count Rumford is similar in principle to the preceding method. This apparatus consists of a worm carried through a vessel of water in a manner similar to the worm of a still. The gas, being previously weighed, prepared, and dried, is raised to 100° by passing it through a similar worm placed in a vessel of boiling water. It is then passed through the worm of the calorimeter and raises the temperature of the water, its own temperature falling. The elevation of the temperature of the water and the fall of the temperature of the gas being observed, data are obtained from which the specific heat of the gas is calculated.

100. Regnault's experiments.—The most accurate determinations of specific heat that have hitherto been published are probably those made by Regnault, by the method of mixtures. The substance to be examined is contained in a basket of fine brass wire, suspended in the middle of an upright cylinder of thin metal. The cylinder is surrounded by a larger concentric cylinder, and this again by a third. By the ebullition of water in a boiler the annular space between the first and second cylinder is kept constantly supplied with steam, which passes through openings near the top of the middle cylinder into the outer annular space comprised between the second and third cylinder, and hence by a waste-pipe to a condenser and back to the boiler. The temperature of the substance in the basket is shown by a thermometer, the bulb of which occupies a cylindrical space left for the purpose in the middle of the basket; the water into which the substance is to be plunged is contained in a small vessel of very thin and highly polished brass, supported

upon three points, and carried by a foot which slides along a groove, so that by a rapid and smooth motion it can be brought directly under the interior cylinder. When in this position, it is protected from heat radiated by the boiler by a double screen, between the two coatings of which a continual circulation of cold water is kept up. The temperature of this calorimeter is indicated by a thermometer, the bulb of which is long enough to reach from just below the surface of the water to very near the bottom.

At the commencement of an experiment the calorimeter is drawn back, and the basket containing the substance to be examined is suspended in the middle of the inner cylinder by a silk thread, the cylinder itself being closed at top and bottom by hollow plugs, to prevent loss of heat. Steam from the boiler being allowed to circulate about the inner cylinder, the substance in the basket is gradually heated to nearly the temperature of boiling water. After a time the thermometer in the basket becomes stationary. The temperature of the water in the calorimeter is then observed by means of a telescope, that of the air being read off at the same time upon another thermometer. The calorimeter is now quickly pushed under the heating apparatus, the plug at the bottom of the inner cylinder removed, and the basket with its contents allowed to fall into the water of the calorimeter, which is immediately drawn back again. The basket is then moved about in the water while an observer watches through the telescope the maximum temperature indicated by the thermometer in the calorimeter.

Let the data of the experiment be as follows :—

Weight of substance in wire basket	= w
„ „ brass wire basket	= w
Specific heat of brass	= s
Temperature of the substance at moment of immersion	= τ
„ „ water in the calorimeter at same moment	= t
Maximum temperature of calorimeter after immersion	= θ
Weight of water in calorimeter	= w'

Then, if the specific heat of the substance = s , we shall have, in accordance with the principles explained in art. 99,

$$w s (\tau - \theta) + w s (\tau - t) = w' (\theta - t)$$

consequently

$$s = \frac{w' (\theta - t) - w s (\tau - \theta)}{w (\tau - \theta)}$$

101. **Regnault's tables of specific heat.**—The following tables give, in a summary form, Regnault's results principally

for inorganic solids. For reasons which will appear afterwards, the tables contain two additional columns, one giving the atomic, and respectively molecular, weights of the substances, the other the product of the specific heat into the atomic, and respectively molecular, weight of each substance. The temperatures between which the determinations were made are only given in Table I. For the substances in Table II. they were in all cases between a temperature approaching 100° C. and a temperature near that of the atmosphere. In the case of substances which are soluble in water, or capable of being chemically acted on by it in any way, the calorimeter was filled with oil of turpentine. The substances are grouped according to chemical composition.

The specific heat of a few substances, which play a part in the experimental arrangement for determining that of the others, viz., brass, glass, oil of turpentine, and water, was determined by preliminary experiments and found to be :—

Substance	Specific Heat	Range of Temperature
Brass	0.09391	between 98° and 12°
Glass	0.19768	" 99 " 14
Oil of turpentine	0.42593	" 98 " 15
Water	1.00800	" 98 " 13

TABLE I.—*Specific Heat of Elementary Bodies.*

Name	Specific Heat	Temperature	Atomic weight	Product of at. weight x sp. heat
Lithium	0.94080	100° to 27°	7 = Li	6.59
Sodium . . . . .	.29340	6 " -32°	23 = Na	6.75
Magnesium . . . . .	.24990	98 " 23	24 = Mg	6.00
Aluminium (sp. h. corrected for 2 per cent. iron impurity) . . . . .	.21430	97 " 14	27.5 = Al	5.89
Phosphorus, liquid . . . . .	.21200	100 " 50	31 = P	6.57
" solid . . . . .	.18870	30 " -10°	" "	5.85
" " . . . . .	.17400	10 " -78°	" "	5.39
" amorphous . . . . .	.17000	98 " 15	" "	5.27
Sulphur, recently melted . . . . .	.20259	98 " 14	32 = S	6.48
" native . . . . .	.17760	99 " 14	" "	5.68
Potassium . . . . .	.16956	0 " -78°	39 = K	6.61
Manganese (containing a trace of silica) . . . . .	.12170	97 " 14	55 = Mn	6.69

TABLE I. (continued).

Name	Specific Heat	Temperature	Atomic Weight	Product of at. weight \times sp. heat
Iron	·11380	$^{\circ}$ 98 to $^{\circ}$ 17	56 = Fe	6·37
Nickel, specimen I., 1840	·10863	99 " 13	58·7 = Ni	6·37
" " II., 1859	·10752	97 " 17	" "	6·31
" " III., 1859	·11080	97 " 12	" "	6·50
Cobalt, " I., 1840	·10696	99 " 12	58·7 = Co	6·28
" " II., 1859	·10620	98 " 10	" "	6·23
" " III., 1859	·10730	97 " 8	" "	6·30
Copper	·09515	98 " 15	63·5 = Cu	6·04
Zinc	·09555	99 " 14	65 = Zn	6·21
Arsenic	·08140	98 " 13	75 = As	6·11
Selenium, metallic	·07616	97 " 21	79 = Se	6·02
" " "	·07446	7 " -18	" "	5·88
" " vitreous	·10310	82 " 19	" "	8·15
" " "	·07468	8 " -24	" "	5·90
Bromine, solid . . .	·08432	-20 " -78	80 = Br	6·75
" " liquid . . .	·11294	58 " 13	" "	
" "	·11094	48 " 10	" "	
" "	·10513	10 " -6	" "	
Molybdenum (impure) .	·07218	98 " 12	96 = Mo	6·93
Rhodium, specimen I. .	·05527	98 " 20	104·4 = Rh	5·77
" " II.	·05803	97 " 11	" "	6·07
Palladium	·05928	98 " 14	106 = Pd	6·28
Silver	·05701	99 " 13	108 = Ag	6·16
Cadmium (containing 1 per cent. impurity) .	·05669	98 " 16	112 = Cd	6·35
Tin	·05623	99 " 12	118 = Sn	6·63
Uranium (impure) . . .	·06190	98 " 10	120 = U	7·43
Antimony	·05077	97 " 12	122 = Sb	6·19
Iodine	·05412	98 " 9	127 = I	6·87
Tellurium	·04737	98 " 18	128 = Te	6·06
Tungsten	·03342	98 " 12	184 = W	6·15
Gold	·03244	98 " 12	196 = Au	6·36
Iridium	·03259	99 " 17	198 = Ir	6·45
Platinum	·03243	99 " 12	198 = Pt	6·42
Osmium	·03113	98 " 19	199·2 = Os	6·20
Mercury, solid . . .	·03192	-40 " -78	200 = Hg	6·38
" " liquid . . .	·03332	98 " 12	" "	6·66
Thallium (according to Lamy)	·03250		204 = Th	6·63
Thallium (according to Regnault) . . .	·03355	100 " 17	" "	6·84
Lead {	·03140	98 " 15	207 = Pb	{ 6·50
Bismuth {	·03065	10 " -78		
	·03084	98 " 13	210 = Bi	6·48

TABLE I. (*continued*).

Name	Specific Heat	Temperature	Atomic Weight	Product of at. weight x sp. heat
Boron, graphitic . . .	·23520	⁰ _{99 to} ⁰ ₁₇	11 = B	2·59
„ crystallised . . .	·25000	100 „ 11	„ „	2·75
Carbon, wood charcoal .	·24150	98 „ 8	12 = C	2·90
„ graphite . . .	·20083	98 „ 12	„ „	2·41
„ diamond . . .	·14687	98 „ 9	„ „	1·76
Silicon, crystallised . .	·17740	99 „ 12	28 = Si	4·97
„ fused . . .	·17500	100 „ 22	„ „	4·90

TABLE II.—*Specific Heat of Inorganic Compounds.*

Name of Substance	Formula	Specific Heat	Molecular Weight	Product of Specific Heat x mol. weight
A. DIATOMIC MOLECULES.				
1. Oxides.				
Protoxide of lead (fused)	PbO	·005089	223	11·35
Oxide of mercury . . .	HgO	·05179	216	11·19
Protoxide of manganese .	MnO	·15701	71	11·15
Oxide of copper . . .	CuO	·14201	79·5	11·19
Oxide of nickel (calcined)	NiO	·15885	74·7	11·87
Magnesia . . .	MgO	·24394	40	9·76
Oxide of zinc . . .	ZnO	·12480	81	10·11
2. Sulphides.				
Protosulphide of iron . .	FeS	·13570	88	11·94
Sulphide of nickle . . .	NiS	·12813	90·7	11·62
„ cobalt . . .	CoS	·12512	90·7	11·36
„ zinc . . .	ZnS	·12303	97	11·93
„ lead . . .	PbS	·05086	239	12·15
„ mercury . . .	HgS	·05117	232	11·87
Stannous sulphide . . .	SnS	·08375	150	12·56
3. Chlorides.				
Chloride of lithium . . .	LiCl	·28213	42·5	11·99
„ sodium . . .	NaCl	·21401	58·5	12·52
„ potassium . . .	KCl	·17295	74·5	12·88
„ silver . . .	AgCl	·09109	143·5	13·07
Mercurous chloride . . .	HgCl	·05205	235·5	12·26
Cuprous . . .	CuCl	·13827	99·0	13·69

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TABLE II. (*continued*).

Name of Substance	Formula	Specific Heat	Molecular Weight	Product of Specific Heat x mol. weight
4. Bromides.	MBr			
Bromide of potassium . .	KBr	·11322	119	13·47
" silver . .	AgBr	·07391	188	13·90
" sodium . .	NaBr	·13842	103	14·26
5. Iodides.	MI			
Iodide of potassium . .	KI	·08191	166	13·60
" sodium . .	NaI	·08684	150	13·03
Mercurous iodide . .	HgI	·03949	327	12·91
Iodide of silver . .	AgI	·06159	235	14·47
Cuprous iodide . .	CuI	·06869	190·5	13·09
B. TRIATOMIC MOLECULES.				
1. Oxides.	MO ²			
Stannic oxide	SnO ²	·09326	150	13·99
Titanic anhydride, artificial	TiO ²	·17164	82	14·07
" " Rutile . .	"	·17082	"	13·97
Silicic anhydride . . .	SiO ²	·19132	60	11·48
Intermediate oxide of antimony	SbO ²	·09535	154	14·70
2. Sulphides.	MS ²			
Iron pyrites	FeS ²	·13009	120	15·61
Stannic sulphide . . .	SnS ²	·11932	182	21·72
Disulphide of Molybdenum	MoS ²	·12334	160	19·73
3. Chlorides.	MCl ²			
Chloride of barium . .	BaCl ²	·08957	208	18·63
" strontium . .	SrCl ²	·11990	158·6	19·02
" calcium . .	CaCl ²	·16420	111	18·23
" magnesium . .	MgCl ²	·19460	95	18·49
" mercury . .	HgCl ²	·06889	271	18·67
" zinc . .	ZnCl ²	·13618	136	18·52
" lead . .	PbCl ²	·06641	278	18·46
" manganese . .	MnCl ²	·14255	126	17·96
Stannous chloride . .	SnCl ²	·10161	189	19·20
4. Iodides.	MI ²			
Iodide of lead	PbI ²	·04267	461	19·65
" mercury . .	HgI ²	·04197	454	19·07
C. TETRATOMIC MOLECULES.				
1. Oxides.	MO ³			
Tungstic anhydride . .	W ₂ O ³	·07983	232	18·52
Molybdic "	MoO ³	·13240	144	19·07

TABLE II. (*continued*).

Name of Substance	Formula	Specific Heat	Molecular Weight	Product of Specific Heat x mol. weight
2. Chlorides.	MCl³			
Chloride of arsenic . . .	AsCl ³	·17604	181·5	31·95
Trichloride of phosphorus	PCl ³	·20922	137·5	28·77
D. PENTATOMIC MOLECULES.				
1. Simple Oxides.	M²O³			
Alumina, corundum . . .	Al ² O ³	·19762	103	20·35
„ sapphire . . .	„	·21732	„	22·38
Specular iron . . .	Fe ² O ³	·16695	160	26·71
Arsenious anhydride . . .	As ² O ³	·12786	198	23·01
Oxide of chromium . . .	Cr ² O ³	·17960	153	27·47
„ bismuth . . .	Bi ² O ³	·06053	468	28·33
„ antimony . . .	Sb ² O ³	·09009	292	26·31
2. Mixed Oxides.	MNO³			
a. Nitrates—				
Nitrate of potassium . . .	KNO ³	·23875	101	24·11
„ sodium . . .	NNaO ³	·27821	85	23·65
„ silver . . .	NAgO ³	·14352	170	24·39
b. Carbonates.				
Carbonate of calcium, Iceland spar . . .	CCaO ³	·20858	100	20·86
Ditto, arragonite . . .	„	·20850	„	20·85
Ditto, saccharoid marble . . .	„	·21585	„	21·58
Ditto, grey . . .	„	·20989	„	20·99
Ditto, white chalk . . .	„	·21485	„	21·48
Carbonate of barium . . .	CBaO ³	·11038	197	21·74
„ strontium . . .	CSrO ³	·14483	147·6	21·38
„ iron . . .	CFeO ³	·19345	116	22·44
3. Sulphides.	M²S³			
Sulphide of antimony . . .	Sb ² S ³	·08403	340	28·57
„ bismuth . . .	Bi ² S ³	·06002	516	30·97
4. Chlorides.	MCl⁴			
Stannic chloride . . .	SnCl ⁴	·14759	260	38·37
Chloride of titanium . . .	TiCl	·19145	192	36·76
E. HEXATOMIC MOLECULES.				
1. Sulphates.	SMO⁴			
Sulphate of barium . . .	SBaO ⁴	·11285	233	26·28
„ strontium . . .	SSrO ⁴	·14279	183·6	26·36
„ calcium . . .	SCaO ⁴	·19656	136	26·73
„ lead . . .	SPbO ⁴	·08723	303	26·43
„ magnesium . . .	SMgO ⁴	·22159	120	26·59

TABLE II. (*continued*).

Name of Substance	Formula	Specific Heat	Molecular Weight	Product of Specific Heat x mol. weight
2. Carbonates.				
Carbonate of potassium .	CM ² O ³	·21623	138	29·84
„ sodium .	CK ² O ³ CNa ² O ³	·27275	106	28·91
F. HEPTATOMIC MOLECULES.				
1. Sulphates.				
Sulphate of potassium .	SM ² O ⁴	·19010	174	33·08
„ sodium .	SK ² O ⁴ SNa ² O ⁴	·23115	142	32·82

102. Necessary Precautions.—In ascertaining the specific heat of bodies by the method of mixtures, we must not overlook the fact that the walls of the vessel, and the thermometer used, participate in the warming. The vessel is usually made of thin sheet metal, copper or silver. If γ be the specific heat of the metal employed, μ the weight of the vessel, the quantity of heat necessary to heat it from t° to r° will be $\mu\gamma(r-t)$. The quantity of heat $\mu\gamma$, which raises the temperature 1° , is called the *water-equivalent* of the vessel. The water-equivalent of the vessel can, of course, be immediately calculated from its weight and the known specific heat of its substance, but that of the thermometer must be determined by experiment. For this purpose it is heated, say by plunging it into heated mercury, about 30° , and then quickly transferred to a weighed quantity of water, and the rise of temperature produced is observed with another delicate thermometer. This, multiplied by the mass of the water, divided by the loss of temperature of the heated thermometer, gives its water-equivalent. If we call this value θ , then we must write the formula of art. 99 thus :

$$s = \frac{W' + \mu\gamma + \theta}{W} \times \frac{(t - T')}{(T - t)}$$

for we must add the water-equivalents of the calorimeter and thermometer, once for all determined, to the net weight of the water used for filling it.

The unavoidable loss of heat from the calorimeter to surrounding objects during the experiment is most easily got rid of by making the initial temperature, as nearly as possible, as

much below the temperature of the room as the final temperature t will be above it. The rise of the temperature which may be expected is determined by a preliminary experiment, or if the specific heat be approximately known it may be calculated with sufficient accuracy; to fulfil this condition with sufficient approximation the change of temperature in the calorimeter must not exceed a moderate quantity (10°). Further, to reduce the radiation and the loss by conduction as much as possible, the vessel should have a bright polished surface, and should be placed upon a badly conducting support, such as three points of wood or crossed silk threads.

103. **Method of cooling.**—Equal weights of two bodies raised to the same temperature and allowed to cool under precisely similar circumstances will occupy different times in cooling through the same number of degrees. In order to ensure the exact fulfilment of these conditions, a multitude of precautions are necessary which cannot be detailed here. The result, however, is that by observing the intervals of time which are necessary for equal volumes of the two bodies to fall one degree we obtain the ratio of the quantities of heat which they lose, and this being determined for equal volumes, the quantities for equal weights may be inferred from the specific gravities of the bodies, and the specific heats will thus be obtained. The substances to be examined are all reduced to an impalpable powder, and filled successively into the same cylindrical silver vessel, gilded and highly polished externally, in the axis of which is the bulb of the thermometer by which the progress of the cooling is to be shown. The silver vessel, supported by the stem of the thermometer, is suspended in the middle of a large brass receiver, coated internally with lampblack, from which the air can be completely removed. This is immersed in water at 40° , and when the thermometer inside the apparatus marks 35° , it is transferred to melting ice. The thermometer is now watched through a telescope, and the instants at which it marks 20° , 15° , 10° , and 5° are noted. If z and z' are respectively the times required by equal weights of two different bodies for cooling through the same range of temperature, say from 10° to 5° , then we shall have the proportion—

Heat lost by first body : Heat lost by second body :: $z : z'$,

Or, $5ws : 5ws' :: z : z'$,

$$\text{hence } \frac{s}{s'} = \frac{z}{z'}$$

This was applied with considerable success by Dulong and Petit, and also by Regnault, who submitted this method to very careful examination and found that it was impossible to obtain results of any value by its application in the case of solids, because the method assumes, which is not quite the case, that the cooling in all parts is equal, and that all substances part with their heat to the silver case with equal facility.

104. **Specific heat of liquids.**—This may be determined either by the method of cooling, by that of mixtures, or by that of the ice calorimeter. In the latter case they are contained in a small metal vessel, or a glass tube, which is placed in the central compartment, and the experiment is then made in the usual manner.

When different liquids are mixed, or when solids are dissolved in liquids, chemical phenomena are generally developed, in consequence of which the specific heat of the mixture differs from that which it would have if the constituents were merely interfused without any change in their thermal qualities. Like the other qualities of the constituents, their specific heats are in this case modified; and the compound is generally found to have a less specific heat than that which would be inferred from the specific heats of its components. When the chemical combination is thus, as it is almost universally, attended by a diminution in the specific heat of the compound as compared with that which would be computed from the specific heats of its components, it is also found that the volume of the mixture is less than the sum of the volumes of its compounds, and that the temperature of the mixture is higher than the common temperature of the liquids mixed.

Thus, for example, if a pint of water and a pint of sulphuric acid, both of the temperature of 14° , be mixed, the mixture will rise to the temperature of 100° , and the volume of the mixture will be considerably less than a quart. The chemical attraction of the particles, therefore, in this and like cases, produces condensation, and, in fact, the same effect ensues as would be produced by compression. The elevation of temperature may be explained in exactly the same manner as when bodies are compressed by mechanical force. The specific heat of the mixture being less than that which is due to its component parts, and the absolute quantity of heat contained in it not being diminished, that quantity will raise it to a much higher temperature than that which it would have had if the specific heats remained unaltered.

The following Table contains the specific heats of the most important liquids, as determined by various observers.

Specific Heats of Liquids.

Substance	Temperature	Specific Heat
Lead	350 to 450	0.0402
Sulphur	120 „ 150	.234
Bismuth	280 „ 380	.0363
Tin	250 „ 350	.0637
Chloride of calcium, crystallised	33 „ 80	.555
Nitrate of sodium	320 „ 430	.413
Nitrate of potassium	350 „ 435	.3319
Mercury	44 „ 24	.0332
Iodine	—	.10822
Bromine	45 to 11	.107
Sulphuric acid	46 „ 21	.343
Wood-spirit	43 „ 23	.645
Alcohol (Kopp)	43 „ 23	.615
„ (Favre and Silbermann)	—	.6438
Fusel-oil	44 to 26	.564
Ethyl	—	.5059
Ether	—	.50342
Formic acid	45 to 24	.536
Acetic „	45 „ 24	.509
Butyric „	45 „ 21	.503
Formate of ethyl	39 „ 20	.313
Acetate of methyl	41 „ 21	.507
Acetate of ethyl	45 „ 21	.496
Butyrate of methyl	45 „ 21	.487
Valerate of methyl	45 „ 21	.491
Acetone	41 „ 21	.530
Benzine	46 „ 19	.450
Oil of mustard	48 „ 28	.432
Oil of turpentine (Favre and Silbermann)	—	.46727

105. **Specific heat of water and ice.**—The specific heat of water at different temperatures has been determined by Regnault, from whose experiments it appears that the quantity of heat expressed in heat units which one gramme of water loses in cooling down from t° to 0° C. is given by the formula

$$q = t + 0.00002 t^2 + 0.0000003 t^3 ;$$

and the specific heat c at the temperature t° , that is to say, the quantity of heat required to raise one gramme of water from t° to $(t+1)^{\circ}$, is

$$c = 1 + 0.00004 t + 0.0000009 t^2$$

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From this formula the following numbers are obtained :—

Specific Heat of Water.

t.	q.	C.	t.	q.	C.
0	0.000	1.0000	150	151.462	1.0262
50	50.087	1.0042	200	203.200	1.0440
100	100.500	1.0130	230	234.708	1.0568

The specific heat of ice is considerably less than that of liquid water. According to Regnault's experiments it is 0.474 between -78° and 0° C., and 0.504 between -20° and 0° according to the experiments of Person and of Desains.

106. *Relation between specific heat and atomic weight.*

—On comparing together the numbers expressing the specific heat of the simple bodies, with those which express their atomic weights or chemical equivalents, Dulong and Petit observed that the one increased in almost the exact proportion in which the other diminished, so that by multiplying them together, a product very nearly constant was obtained.

From this it would follow, upon the atomic hypothesis, that the specific heats of the atoms of all the simple bodies are equal. For in equal weights, the number of constituent atoms will be great in proportion as the individual weights of these atoms are small. The number of atoms, therefore, in equal weights, being inversely proportional to the weights of the atoms, and the specific heats being also inversely proportional to the weights of the atoms, it follows that the specific heats of equal weights are in the proportion of the number of atoms contained in those weights, and that, consequently, the specific heats of the component atoms must be equal.

This, therefore, is a quality in which the atoms of all simple bodies, however they may differ in other respects, agree—that their temperatures are equally affected by the same quantity of heat.

That this law is not rigorously exact, however, is proved by the fact that the specific heat of the same body is different at different temperatures and in different states.

It has resulted from the researches of Regnault, that the relation between the specific heats and atomic weights, observed by Dulong and Petit in the simple bodies, also prevails among compound bodies ; and that, in general, in all compound bodies of the same atomic composition and having similar chemical con-

stitution, the specific heat is in the inverse ratio of the atomic weight. The law is, however, subject to some qualifications and exceptions.

107. Relations between the specific heats of liquid and solid bodies, and their coefficients of expansion at different temperatures.—The specific heat of any substance includes, not only the portion of heat required to cause in it a given alteration of temperature, but also the quantity of heat which is expended in modifying its condition of molecular equilibrium, and whose most obvious external effect is an alteration of the volume of the substance. Although no certain data exist for calculating the ratio of these two parts of the total specific heat, except in the case of gases, it is nevertheless probable that the former part, or the real specific heat of a substance, remains the same for all conditions. Hence, variations in the total or apparent specific heat must be supposed to result from variations in the amount of heat expended in overcoming the molecular forces.

In sensibly perfect gases, the consumption of heat in this manner is the same at all temperatures, and so small as to be negligible; accordingly, both the real and apparent specific heats of gases are constant at all temperatures. On the other hand, the molecular changes which accompany alterations of temperature in liquid and solid bodies are such as require the expenditure of very considerable quantities of heat to produce them. These changes doubtless consist in alterations of the relative position or arrangement of the molecules, but of what precise kind we have no means of ascertaining, since the only measurable portion of the total effect is the externally visible change of volume.

This change of volume cannot be taken as in every case a measure of the amount of molecular work performed by the heat independently of causing alteration of temperature; for, as we know, the communication of heat to water below 4°C . causes a change of bulk of the opposite kind to that which it occasions above that temperature; but we may nevertheless probably admit without great error that, as a general rule, the proportion of the total quantity of heat required to raise the temperature of a given substance 1° , which is consumed in producing molecular changes, is greatest at those points of the thermometric scale at which the greatest amount of expansion accompanies a rise of temperature of 1° , and is least at those points at which the corresponding expansion is least. If this supposition be admitted, it accounts satisfactorily for the fact that both the specific heats of solid and liquid bodies and their coefficients of

expansion increase, as a rule, with rise of temperature ; and that both these properties vary most rapidly in the neighbourhood of those temperatures at which changes of the state of aggregation occur.

108. **Relation of specific heat to various phenomena.**—

The specific heat of bodies diminishes as their density is increased, and *vice versâ*. This partly explains the fact that mechanical compression will, without any addition of heat, raise the temperature. If metal be hammered it becomes hot, and it is even affirmed that iron has been rendered incandescent in this manner.

The syringe in which compressed air is made to inflame tinder acts partly on this principle. The air compressed under the syringe acquires a greatly diminished specific heat, and, consequently, although it has received no heat from any external source, the same heat which before compression only gave it the common temperature of the surrounding medium, gives it, after compression, a temperature high enough to produce the ignition of a highly inflammable substance like tinder.

The circumstance that rarefied air has an increased capacity for heat will partly explain the very low temperatures which are known to exist in the higher regions of the atmosphere.

This effect becomes extremely sensible when we ascend to any considerable height, as has been manifest in ascending high mountains and in balloons. Upon these occasions, the cold has sometimes become so intense that mercury in the thermometer has been frozen. In strata so elevated that the permanent temperature of the air is below 0° , water cannot continue in the liquid state ; it exists there only in the form of ice or snow, and we accordingly find eternal snow deposited upon those parts of high mountains which exceed this limit of temperature.

The level of that stratum of air which by its rarefaction reduces the temperature to 0° is called the *line of perpetual snow*, and its position in different parts of the earth varies, the height increasing generally in approaching the equator, and falling towards the poles. The various conditions which affect the position of this line in different parts of the earth are explained further on.

The elevation of temperature produced by the compression of gases has supplied means of reducing some of them to the liquid form. Gases may be considered as vapours raised from liquids, which have received, after their separation from the liquid which produced them, a large additional supply of heat. It is to the effects of this surplus heat that their per-

manent maintenance in the gaseous state must be ascribed. If, by any means, they can be deprived of this surplus heat, so that no heat shall be left in them except that which they received in the process of vaporisation, any further loss of heat would necessarily cause them to return, in more or less quantity, to the liquid form. But if the specific heat be so great that, notwithstanding all the heat transmitted to the gas after taking the vaporous form, it still has attained only the common temperature of the atmosphere, it is clear that it can only be restored to the liquid form either by reducing its temperature to an immense extent, by the application of freezing mixtures, or by first raising its temperature by high degrees of mechanical compression, and then allowing it to fall to the temperature of surrounding objects, or, in fine, by combining both these methods. Thus atmospheric air, at the common temperature of 50° F., being compressed into a diminished volume, in the proportion of 10000 to 3, its temperature would be raised through an extent of 13500 degrees, according to Leslie's experiment. This heat being immediately abstracted by the surrounding objects, its temperature would fall to that of the medium in which it is placed. Thus, without the application of a freezing mixture, or other means of cooling, an immense abstraction of heat may be effected; and this may be continued so long as a mechanical force adequate to the further compression of the gas could be exerted. Freezing mixtures may then be applied to the further reduction of temperature. Methods of producing the liquefaction of certain gases will be explained hereafter.

The explanation of various phenomena given in this and the following article may serve in the mean time, but will receive considerable modifications and extensions hereafter in the chapter on the dynamical theory of heat, in which the relation between heat and mechanical work is discussed on the basis of more recent investigations.

109. Specific heat of gases and vapours.—In general no practicable force can prevent the dilatation of solids and liquids when their temperature is elevated. This, however, is not the case with gases and vapours, which, when heat is imparted to them, may either be permitted to expand under a given pressure, like solids and liquids; or may be confined to a given volume, which they will continue to fill in consequence of their elasticity, however their temperature may be lowered, and which they will not exceed, however their temperature may be raised. In this case, the heat imparted or abstracted is manifested by a

corresponding change of pressure of the gas or vapour instead of dilatation or contraction.

By the specific heat of a gas or vapour may thus be understood its *specific heat when subject to a constant pressure*, that is, when it is allowed to expand or contract; while on the other hand we may apply the term to the heat necessary to raise the gas or vapour one degree, *when confined within a constant volume*. This last has, for distinction, been called the *relative heat*.

The specific heat of a gas or vapour under a constant pressure is greater than under a constant volume. This would follow from the following considerations, but the important bearing which the fact has in connection with recent views on the nature of heat will be seen further on. Suppose a given quantity of gas to have had its temperature raised t degrees, while the pressure remained constant; this increase of temperature will have been accompanied by a certain increase of volume. If now the gas were compressed again, so as to restore it to its original volume, the temperature of the gas will rise in consequence of the compression by an additional number of degrees, which we will denote by t' . The gas is now obviously in the same condition as if it had been heated but not been allowed to expand. Hence the same quantity of heat which was required to raise the same weight of gas through t degrees while the pressure was constant and the volume altered, raised the temperature through $t + t'$ degrees while the volume remained constant, but the pressure varied. Hence the specific heat of a gas under constant pressure is greater than the specific heat under constant volume in the proportion of $t + t' : t$.

For atmospheric air, oxygen and hydrogen, the ratio of the specific heat under a given pressure is to the specific heat in a given volume as 1.421 to 1. For carbonic acid it is 1.338; for carbonic oxide, 1.428; for nitrous oxide, 1.343; and for olefiant gas, 1.240.

The expansion of high-pressure steam escaping from the safety valve forms a remarkable instance that the same quantities of heat may give very different temperatures to a body, in different states of density. Steam produced under a pressure of 21 atmospheres has the temperature of 215°C . When such steam escapes into the atmosphere, it undergoes a prodigious expansion without losing heat, and suffers a considerable fall in temperature.

Under equal pressures the simple gases have the same specific heat. This uniformity, however, does not prevail among the compound gases, as will appear by the tables of specific heat of the gases.

110. Formula for the variation of specific heat consequent on change of pressure.—The law according to which the same gas varies its specific heat with the change of pressure or density is, according to Poisson, expressed by the formula—

$$s = s' \times \left(\frac{30}{P} \right)^{1 - \frac{1}{k}},$$

where P expresses the pressure in inches of mercury, s' the specific heat under the mean pressure of 30 inches, and k the constant number, which expresses the ratio of the specific heat under a given pressure to the specific heat under a given volume, which, in the case of common air and the simple gases, is 1·421, as has been already explained.

111. Influence of difference in the physical condition.—It results from Regnault's determinations of the specific heats of gases and vapours, that the specific heat of a given weight of a gas which obeys Boyle's law does not alter with variations either of temperature or of pressure. This was found to be true of atmospheric air between the temperatures of -20° and $+225^{\circ}$, and at pressures varying from 1 to 12 atmospheres. Consequently the specific heat of a given volume of air, or other non-condensable gas, varies directly as its density. In gases which do not follow Boyle's law, this regularity does not exist: thus the specific heat of carbonic anhydride is found to increase perceptibly as its temperature rises, being 0·18427 between -30° and 10° , and 0·20246 between 10° and 100° , and 0·21692 between 10° and 210° , as compared with that of an equal weight of water.

The following table gives the specific heat of various gases and vapours examined by Regnault, compared, first, with an equal weight of water taken as unity; secondly, with that of an equal volume of air referred as before to its own weight of water as unity. The latter series of numbers is obtained by multiplying the numbers expressing the specific heats of equal weights of the various gases or vapours, by their respective densities referred to that of air as 1.

Name of Gas	Specific Heats	
	Equal weights	Equal volumes
Air	0·2374	0·2374
Oxygen	·2175	·2405
Nitrogen	·2438	·2370
Hydrogen	3·4090	·2359

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Name of Gas	Specific Heats	
	Equal weights	Equal volumes
Chlorine	0'1210	'2962
Bromine	'0555	'2991
Nitrous Oxide	'2238	'3447
Nitric Oxide	'2315	'2406
Carbonic Oxide	'2450	'2370
Carbonic Anhydride	'2163	'3307
Sulphurous Anhydride	'1544	'3414
Hydrochloric Acid	'1845	'2333
Sulphydric Acid	'2431	'2857
Ammonia	'5083	'2996
Marsh gas	'5929	'3777
Olefiant gas	'4040	'4106
Name of Vapour		
Water	'4805	0'2984
Sulphide of carbon	'1570	'4140
Alcohol	'4534	'7171
Ether	'4810	1'2296
Chloride of ethyl	'2737	0'6096
Bromide of ethyl	'1816	'6777
Sulphide of ethyl	'4005	1'2568
Cyanide of ethyl	'4261	'8105
Chloroform	'1566	'6565
Acetate of ethyl	'4008	1'2184
Acetone	'4125	'8341
Benzine	'3754	1'0114
Oil of turpentine	'5061	2'3776
Stannic Chloride	'0939	'8639

Comparing these values with those given for some of the same substances in the previous table, it appears that the specific heat of the same body is commonly greater in the liquid than in the solid state, and always less in the gaseous than in the liquid state.

On examining the numbers above given for the specific heats of different bodies, it will be seen that the specific heat of a substance is not altogether an absolute and unchangeable property; on the contrary, it will be evident that this property, in one and the same substance, is capable of considerable variation, depending (a) on the physical structure of the substance, (b) on its temperature, (c) on its state of aggregation. In illustration of this remark, it will be sufficient to refer to the specific heats of carbon, silicon, selenium, sulphur, phosphorus, alumina, and carbonate of calcium, as given in the previous table, in evidence of the influence of differences of physical condition.

112. Summary of laws regulating the specific heat of bodies.—As has been already stated, many of the facts referring to specific heat will have to be further considered in the chapter on the theory of heat. It will therefore be useful to recapitulate the principal laws for future reference.

A. SOLIDS. 1. *The specific heat of a solid is greater at a high temperature than at a low one.* This is shown by such experimental results as the following, due to Dulong and Petit.

Substance	Mean Specific Heat.	
	Between 0° and 100° C.	Between 0° and 300° C.
Iron	0·1098	0·1218
Zinc	0·0927	0·1015
Antimony	0·0507	0·0549
Silver	0·0557	0·0611
Copper	0·0949	0·1013
Platinum	0·0355	0·0355
Glass	0·1770	0·1990

Platinum forms within the limits of these experiments an apparent exception.

2. *The specific heat of the same substance differs with the density, the state of aggregation, and is different for different allotropic states.*—In general, whatever augments the density diminishes the specific heat, and whatever diminishes the density augments the specific heat. It depends possibly on this fact, that in consequence of expansion, which diminishes the density of a substance, the specific heat at a higher temperature is greater than at a lower. The following table exhibits the specific heat of carbonate of lime, sulphur, and carbon, in different states of aggregation and allotropism.

Carbonate of Lime.

Aragonite	0·2085
Iceland spar	0·2085
Chalk	0·2148
White marble	0·2158

Sulphur.

Recently melted	0·1844
Melted less than two months	0·1803
Melted less than two years	0·1764
Natural crystals	0·1776

Carbon.

Animal charcoal	.	.	.	.	.	0.2608
Wood charcoal	.	.	.	.	.	0.2415
Coke	.	.	.	.	.	0.2008
Graphite	.	.	.	.	.	0.2018
Diamond	.	.	.	.	.	0.1468

B. LIQUIDS. 1. *A substance when liquid has in general a greater specific heat than when solid.* The specific heat of ice is only one half that of water.

2. *The specific heat of liquids increases in general with the temperature, and at a rate exceeding that of solids.* This is shown by the following comparative little table, which also shows that platinum forms no exception to the general law.

<i>Water (Regnault).</i>				<i>Platinum (Pouillet).</i>			
From 0°	to 40°	.	1.0013	From 0°	to 100°	.	0.0335
" 0°	" 80°	.	1.0035	" 0°	" 300°	.	0.0343
" 0°	" 120°	.	1.0067	" 0°	" 500°	.	0.0352
" 0°	" 160°	.	1.0109	" 0°	" 700°	.	0.0360
" 0°	" 200°	.	1.0160	" 0°	" 1000°	.	0.0373
" 0°	" 230°	.	1.0204	" 0°	" 1200°	.	0.0382

C. GASES. 1. *The same body has a higher specific heat in the liquid than in the solid state, but in the condition of a gas its specific heat is less than when it is liquid.* The specific heat of water is more than twice as great as that of steam.

2. *The specific heat of a given weight of an approximately perfect gas does not vary with the temperature of the gas.*

3. *The specific heat of a given weight of such a gas is independent of its pressure or density, or, the specific heat of a given volume varies as its density.*

4. *The specific heats of equal volumes of simple and incondensable gases are equal.* This law holds also for compound gases, which are formed without condensation, such as hydrochloric acid gas and nitric oxide.

5. *These laws do not hold for condensable gases.* The specific heat of carbonic acid increases with the temperature.

CHAPTER VII.

LIQUEFACTION AND SOLIDIFICATION.

113. Thermal phenomena attending liquefaction.—It has been already explained, that, in general, when heat is imparted in sufficient quantity to a solid body, such body will at a certain point pass into the liquid state; and when it is abstracted in sufficient quantity from a liquid, the liquid at a certain point will pass into the solid state.

Certain thermal phenomena of great interest and importance are developed in the progress of these changes, which it will now be necessary to explain.

Let us suppose that a mass of ice or snow, at the temperature of -6° is placed in a vessel and immersed in a bath of quicksilver, under which spirit-lamps are placed. Let one thermometer be immersed in the ice or snow, and another in the mercury. Let the number and flame of the lamps be so regulated that the thermometer in the mercury shall indicate the uniform temperature of 95° . The mercury imparting heat to the vessel containing the ice will first cause the ice to rise from -6° to 0° , which will be indicated by the thermometer immersed in the ice; but when that thermometer has risen to 0° it will become stationary, and the ice will begin to be liquefied. This process of liquefaction will continue for a considerable time, during which the thermometer will continue to stand at 0° ; at the moment that the last portion of ice is liquefied it will again begin to rise. The coincidence of this elevation with the completion of the liquefaction may be easily observed, because ice, being lighter, bulk for bulk, than water, will float on the surface, and so long as a particle of it remains unmelted it will be visible.

Now it is evident that, during this process, the mercury maintained at 95° constantly imparts heat to the ice; yet, from the moment the liquefaction begins until it is completed, no increase of temperature is exhibited by the thermometer immersed in the ice. If during this process no heat were received by the ice from the mercury, the lamps would cause the temperature of the mercury to rise above 95° , which may be easily proved by withdrawing the vessel of ice from the mercurial bath during the process of liquefaction. The moment it is withdrawn, the thermometer immersed in the mercury, instead of remaining fixed at 95° , would immediately begin to rise, although the

action of the lamps remained the same as before ; from which it is obvious that the heat, which on the removal of the ice causes the mercury to rise above 95° , was before imparted to the melting ice.

It appears, therefore, that the heat which is received by the melting ice during the process of liquefaction is *latent* in it, being incapable of affecting the thermometer or the senses.

If the hand be plunged in the ice at the moment it begins to melt and at the moment that its liquefaction is completed, the sense of cold will be precisely the same, notwithstanding the large quantity of heat which must have been imparted to the ice during the process of liquefaction.

114. Heat latent in liquefaction.—The quantity of heat which is absorbed and rendered latent in the process of liquefaction can be directly ascertained by the calorimeter of Laplace and Lavoisier. To ascertain this in the case of ice, it is only necessary to place a pound of water at any known temperature in the apparatus, and observe the weight of ice it will dissolve in falling to any other temperature. In this way it will be found that in falling through $79^{\circ}\cdot25$ it will dissolve a pound of ice ; and in general, any proposed weight of water, in falling through this range of temperature, will give out as much heat as will dissolve its own weight of ice.

Hence it is inferred that when ice is liquefied, it absorbs and renders latent as much heat as would be sufficient to raise its own weight of water from 0° to $0^{\circ} + 79^{\circ}\cdot25 = 79^{\circ}\cdot25$.

The latent heat of water has for the last half-century been estimated a degree or two less, that having been the result of the experimental researches of Lavoisier and Laplace. Dr. Black's estimate was 140° , and that of Cavendish 150° on Fahrenheit's scale. A series of experiments have been made, under conditions of greater precision, by MM. de la Provostaye and Desains, from which the above value has been derived.

The most recent determination has been made by Bunsen, with his ice-calorimeter. The latent heat of water was found by him to be $80^{\circ}\cdot025$.

Dr. Black, who first noticed this remarkable fact, inferred that ice is converted into water by communicating to it a certain *dose* of heat, which enters into combination with it in a manner analogous to that which takes place when bodies combine chemically. The heat thus combined with the ice losing its property of affecting the senses or the thermometer, the phenomenon bears a resemblance to these cases of chemical combination in which the constituent elements change their sensible properties when they form the compound.

115. Latent heat rendered sensible by congelation.—If it be true that water is formed by the combination of a large quantity of heat with ice, it would necessarily follow that, in the reconversion of water into ice, or in the process of congelation, a corresponding quantity of heat must be disengaged. This fact can be easily established by reversing the experiment just described.

Let us suppose that a vessel containing water at 15° is immersed in a bath of mercury at the temperature of 15° below the freezing point. If one thermometer be immersed in the mercury and another in the water, the former will gradually rise and the latter fall, until the latter indicates 0° . This thermometer will then become stationary, and the water will begin to freeze; meanwhile the thermometer immersed in the mercury will still rise, proving that the water while it freezes continually imparts heat to the mercury, although the thermometer immersed in the freezing water does not fall. When the congelation is completed, and the whole quantity of water is reduced to the solid state, then, and not until then, the thermometer immersed in the ice will again begin to fall. The thermometer immersed in the mercury will rise without interruption, until the two thermometers meet at some temperature below 0° .

It is evident from this, that the heat which was latent in the water while in the liquid state is gradually disengaged in the process of congelation; and since the temperature of the ice remains the same as that of the water before congelation, the heat thus disengaged must pass to some other object, which in this case is the mercury.

When congelation takes place under ordinary circumstances, the latent heat which is disengaged from the water which becomes solid is in the first instance imparted to the water which remains in the liquid state. When this water passes into the solid state, the heat which is disengaged from it is transmitted to the adjacent water which remains in the liquid state; and so on.

116. Other methods of determining the latent heat of water.—The latent heat of water may be further determined experimentally as follows. Let two equal vessels, one containing a pound of ice at 0° , and the other containing a pound of water at 0° , be both immersed in the same mercurial bath, maintained by lamps or otherwise at the uniform temperature of 300° , and let thermometers be placed in the ice and the water. The ice will immediately begin to melt, and the thermometer immersed in it will remain stationary. The thermometer immersed in the water will, however, at the same time begin to rise. When the liquefaction of the ice has been completed, and

the thermometer immersed in it just begins to rise, the thermometer immersed in the water will be observed to stand at $79^{\circ}25$. It follows, therefore, supposing the ice and the water to receive the same quantity of heat from the mercury which surrounds them, that as much heat is necessary to liquefy a pound of ice as is sufficient to raise a pound of water from 0° to $79^{\circ}25$, which is $79\cdot25$ thermal units; a result which confirms what has been already stated.

The following experiments will further illustrate this important fact.

First let a pound of ice at 0° be placed in a vessel, and let a pound of water at $79^{\circ}25$ be poured into the same vessel. The hot water will gradually dissolve the ice, and the temperature of the mixture will rapidly fall; when the ice has been completely dissolved, the water formed by the mixture will have the temperature of 0° . Thus, although the pound of warm water has lost $79^{\circ}25$, the pound of ice has received no increase whatever of temperature. It has merely been liquefied, but retains the same temperature as it had in the solid state.

That it is the process of liquefaction alone which prevents the heat received by the ice when melted from being sensible to the thermometer, may be proved by the following experiment.

Let a pound of water at 0° be mixed with a pound of water at $79^{\circ}25$, and the mixture will have the temperature of $39^{\circ}62$, exactly intermediate between the temperatures of the compounds. But if the pound of water at 0° had been solid instead of liquid, then the mixture would have had, as already explained, the temperature of 0° . It is evident, therefore, that it is the process of liquefaction; and it alone, which renders latent or insensible all that heat which is sensible when the pound of water at 0° is liquid.

117. Liquefaction and congelation always gradual.—It might be supposed that water at 0° would pass at once from the liquid to the solid state, on losing the least portion of heat; and that, on the other hand, a mass of ice would pass instantly from the solid to the liquid state, on receiving the least addition of heat. What has been just explained, however, shows that this sudden transition from the one state to the other cannot take place.

When a mass of water losing heat gradually is reduced to 0° , small portions of ice are formed, which give out their latent heat to the surrounding liquid, and for the moment prevent its congelation. As this liquid parts with its heat to surrounding objects, more ice is formed, which, in like manner, disengages its

latent heat, and communicates it to a portion of the water still remaining liquid, thus tending to raise its temperature and keep it in the liquid state. The rapidity of the congelation will depend on the rate at which the uncongealed portion of the water can impart its heat to the surrounding air and other adjacent objects.

The same principles explain the gradual process of the liquefaction of ice. A small portion of ice first receives heat from some external source, and having received as much heat as would raise its own weight of water through $79^{\circ}\cdot 25$ of the thermometric scale, it becomes liquid. Then an additional portion of ice receives the same addition of heat, and is likewise rendered liquid; and so the process goes on, until the whole mass of ice is liquefied.

It is possible, under certain circumstances, to maintain water in the liquid state below the freezing point. If a vessel of water be carefully covered up, free from agitation, and exposed to a temperature of -8° , it will gradually fall to that temperature, still remaining in the liquid state; but if it be agitated, or a particle of ice or other solid body be dropped into it, its temperature will suddenly rise to 0° , and a portion of it will be converted into ice.

The explanation of this fact is easy if it be considered that the portion of the liquid which is thus suddenly solidified disengages its latent heat, which is communicated to that part of the water which still remains liquid, and raises it from -8° to 0° , and the remainder of the heat thus disengaged becomes sensible instead of being latent in the ice itself, whose temperature it raises from -8° to 0° . It follows, from what has been already explained, that the entire quantity of latent heat disengaged in this case would be sufficient to raise as much water as is equal in weight to the ice which has been formed through $79^{\circ}\cdot 25$, or what is the same, it would raise nearly 10 times this quantity of water through 8° . Now in the present case the whole quantity of water in the vessel, including the frozen part, has in fact been raised 8° , and it would follow, therefore, that the frozen portion should constitute one part in 10 of the whole mass.

This has been proved experimentally by Thomson, who showed that when water cooled without congelation to -8° was suddenly agitated, a portion was congealed which bore the proportion to the whole quantity just mentioned, that is to say 8 parts in $79\cdot 25$ of the whole mass. He found likewise that the same result was attained when the water cooled to any other temperature below 0° without congelation. Thus when it cooled

to -4° , and was then agitated, it was found that the 20th part of the whole mass was congealed, and so on.

118. **Useful effects produced by latent heat.**—The great quantity of heat absorbed by ice when it melts, and given out by water when it freezes, subserves to the most important uses in the economy of nature. It is from this cause that the ocean, seas, and other large natural collections of water are most powerful agents in equalising the temperature of the inhabited parts of the globe. In the colder regions, every ton of water converted into ice gives out and diffuses in the surrounding region as much heat as would raise a ton of liquid water from 0° to $79^{\circ}25$; and, on the other hand, when a rise of temperature takes place, the thawing of the ice absorbs a like quantity of heat: thus, in the one case, supplying heat to the atmosphere when the temperature falls; and, in the other, absorbing heat from it when the temperature rises. Hence we see why the variations in climate are less on the sea-coasts and on islands than in the interior of large continents.

119. **Latent heat of other bodies.**—The thermal phenomena explained above with reference to water belong to a general class, and are common, with certain modifications, to all solids which are transformed into liquids by the addition, and to all liquids which are transformed into solids by the abstraction, of heat. Thus, if a mass of tin have its temperature raised by the addition of heat until it attain the temperature of 235° , it will then become stationary, notwithstanding it receive further increments of heat; but the moment it becomes stationary, its fusion will begin, and it will continue steadily at the temperature of 235° until it be completed; but the moment the last particle of tin has been melted, its temperature will begin to rise.

In the same manner, if lead be submitted to an increase of temperature, it will begin to liquefy when it reaches the temperature of 334° ; and notwithstanding the additional quantities of heat imparted to it, its temperature will not rise above 334° until its fusion is completed. In a word, all metals whatever, and in general all solids which by elevation of temperature are fused, undergo, during the process of fusion, no elevation of temperature; the heat imparted to them during this process becoming latent in them, since it does not affect the thermometer.

This heat is called the *latent heat of fusion*, and its quantity for each body is determined by means similar to those already explained for water.

120. **Points of fusion.**—Different solids are fused at different temperatures, but the same solid is always fused at the same temperature, which temperature is called its *point of fusion*.

This point of fusion constitutes, therefore, a specific character of the solid. The quantity of heat rendered latent during the fusion of different metals is different, but always the same for the same metal. This quantity is generally estimated or expressed by the number of degrees which it would raise the temperature of a pound of water, supposing a pound of the body in question to undergo the change from the solid to the liquid state. In the same manner, all liquids which, by the loss of heat, are converted into solids, have a certain point, the same for each liquid, but different for different liquids, at which they pass into the solid form. This point is called their *point of solidification*, or their freezing point. It is customary to apply the latter term only to such bodies as at common temperatures are found in the liquid state.

The point at which a body in the liquid state solidifies is the same as that at which the same body in the solid state is liquefied; the points, therefore, of solidification or congelation are the same as the points of fusion or liquefaction for the same bodies. Thus, the point of fusion for ice is the same as the freezing point for water.

Two conditions are therefore necessary to the fusion of a solid body: first, its temperature must be raised to the point of fusion; and, secondly, it must receive a certain quantity of heat, called its heat of fusion, which will become latent in it when the fusion has been completed.

In like manner two conditions are necessary to the congelation or solidification of a liquid: first, it must be reduced to its freezing point; and, secondly, it must be deprived of a certain quantity of heat, which exists latent in it, and maintains it in the liquid state.

The experimental laws of fusion may hence be enunciated thus:—

I. *Every substance begins to fuse at a certain temperature, which is invariable for each substance if the pressure be constant.*

II. *Whatever be the intensity of the source of heat, from the moment fusion commences the temperature of the body ceases to rise, and remains constant until the fusion is complete.*

In the following table are given the points of fusion of the several bodies named in the first column:—

The authorities are indicated as follows:—

Clarke, Cl.	Irvine, I.
Pouillet, P.	Ermann, E.
Vauquelin, V.	Crichton, Cr.
Daniell, Da.	Dumas, Du.
Murray, M.	Guy Lussac, G.L.
Guyton Morveau, G.	Thénard, T.

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Table showing the Point of Fusion of various Substances in Degrees of Fahrenheit's Thermometer.

Names of Substances	Degrees of Fahr.	Authorities
Platina	3082	Cl. P., V.
English wrought iron	2912	
French ditto	2732	
Steel (least fusible)	2552	
" (most fusible)	2372	
Cast manganese	2282	P.
" " brown, fusible	2192	
" " " very fusible	2012	
" " white, fusible	2012	
" " " very fusible	1922	
Gold, very pure	2282	Da.
" money	2156	
Copper	1922	
Brass	1859	
Silver, very pure	1832	
Bronze	1652	P.
Antimony	810	
Zinc	700	M.
	705	G.
	680	P.
	608	P.
Lead	590	I.
	592	G.
	509	E.
	505	P.
Bismuth	477	I.
	480	C.
	512	G.
	446	P.
Tin	442	C.
	433	E.
Alloy 5 parts tin, 1 part lead	381	P.
Alloy 4 parts tin, 1 part lead	372	
Alloy 3 parts tin, 1 part lead	367	
Alloy 2 parts tin, 1 part lead	385	
Alloy 1 part tin, 1 part lead	466	
Alloy 1 part tin, 3 parts lead	552	
Alloy 3 parts tin, 1 part bismuth	392	
Alloy 2 parts tin, 1 part bismuth	333'9	
Alloy 1 part tin, 1 part bismuth	286'2	
Alloy 4 parts tin, 1 part lead, 5 parts bismuth	246	
Sulphur	237	Du.
	226	
	225	
Iodine	212	P.
Alloy 2 parts lead, 3 parts tin, 5 parts bismuth	212	
Alloy 5 parts lead, 3 parts tin, 8 parts bismuth	212	
Alloy 1 part lead, 1 part tin, 4 parts bismuth	201	

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Table showing the Point of Fusion, &c.—continued.

Table of Substances	Degrees of Fahr.	Authorities
Soda	194	G.L., T., P.
Potash	162	G.L., T.
Phosphorus	136	} P.
Stearic acid	109	
Wax, bleached	100	
„ unbleached	158	} M.
Margaric acid	154	
Stearine	142	
Spermaceti	131	} P.
Acetic acid	to	
Tallow	140	
Ice	120	
Oil of turpentine	to	
Mercury	109	
	120	
	113	
	92	
	32	
	14	
	-38'2	

Table of Fusing-points in Centigrade Degrees.

Names of Substances	Degrees of Cent.	Names of Substances	Degrees of Cent.
Wrought iron	1600	Iodine	114
Steel	1300	Selenium	217
Cast iron (grey)	to	Sodium	95'6
„ (white)	1400	Potassium	62'5
Gold (pure)	1100	Stearic acid	70
Copper	to	Wax, bleached	68
Silver	1200	„ unbleached	61
Cadmium	1050	Tallow	33
Antimony	to	Spermaceti	47'7
Zinc	1100	Paraffin	46'3
Lead	1200	Phosphorus	44
Bismuth	1090	Butter	33
Tin	1000	Olive oil	10
Sulphur	500	Linseed oil	1
	425	Ice	0
	423	Oil of almonds	- 9
	334	Oil of turpentine	-10
	270	Bromine	-24'5
	235	Mercury	-38'8
	115		

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121. **Alloys.**—It is found that alloys composed of a mixture of two or more metals, in certain proportions, frequently liquefy at a much lower temperature than either of the constituents. This will be seen on reference to the above table, and still more by inspection of the following table, which gives some of the most recent researches.

Table of Fusing-points of some Alloys.

Lead (Fusing point, 334° C.)	Bismuth (Fusing point, 270° C.)	Tin (Fusing point, 235° C.)	Fusing point of Alloy.
1 part	0 part	1 part	189°
1 "	0 "	1·5 "	169
1 "	0 "	2 parts	171
1 "	0 "	3 "	180
1 "	0 "	4 "	186
1 "	0 "	5 "	192
1 "	0 "	6 "	194
1·5 "	0 "	1 part	211
2 parts	0 "	1 "	227
3 "	0 "	1 "	250
4 "	0 "	1 "	259
5 "	0 "	1 "	267
6 "	0 "	1 "	270
8 "	8 parts	3 parts	94·5
8 "	8 "	8 "	123·3
16 "	8 "	12 "	140·0
30 "	8 "	24 "	119·0

Thus a solder composed of 4 parts of lead and 6 of tin fuses at 336° on Fahrenheit's scale. An alloy composed of 8 parts of bismuth, 5 of lead, and 3 of tin, liquefies at a temperature below that of boiling water; and an alloy composed of 496 bismuth, 310 lead, 177 tin, and 26 mercury, fuses at 162°·5 F. If a thin strip of this alloy be dipped into water that is nearly boiling hot, it will melt like wax. The same will obviously happen with the alloy, mentioned in the above table, which consists of 8 parts of lead, 8 parts of bismuth, and 3 parts of tin, and the melting point of which is 94°·5 C. This alloy is often alluded to as *Rose's fusible metal*. Another alloy, called *Wood's fusible metal*, consisting of 2 parts of cadmium, 2 of tin, 4 of lead, and 8 of bismuth, melts even at a temperature of between 66° and 71°. It may be dropped in the melted state upon the open palm of the hand without the least inconvenience.

Some bodies, like water, pass from the complete solid to the

complete liquid state without passing through any intermediate degrees of aggregation, while others, like wax, tallow, and butter, become soft at temperatures considerably below those at which they are liquefied; and there are others, like glass and some of the metals, which never, at any temperature, attain absolute fluidity.

122. **Sulphur.**—Sulphur also presents some curious exceptional circumstances in its state of aggregation at different temperatures. If heat be gradually and slowly imparted to it, it will be fused and become very fluid at 115° . If the supply of heat be continued, it will change its colour at 160° , and become red and viscous and considerably less fluid at 220° . At length, heat being further supplied, and its temperature being raised from 220° to 400° , it will become altogether red, opaque, and acquire the consistency of a thick paste. At 440° the mass is converted into a red vapour.

123. **Solutions.**—The freezing points of liquids are generally lowered when solids are dissolved in them. Thus, when salt is dissolved in water, the freezing point of the solution is always below 0° , and its distance below it depends on the quality and quantity of salt in solution.

The strong acids generally freeze at much lower temperatures than water, and if they be mixed with water, the freezing point of the mixture will hold an intermediate position between those of water and the pure acid. The freezing points of the acids themselves vary with their strength, but not according to any known or regular law.

124. **Latent heat of fusion.**—The latent heat of fusion has not been extensively investigated. *M. Person* has, however, determined it for the bodies named in the following table. The unit of the numbers expressing the latent heat is the quantity of heat necessary to raise the same weight of water from 0° to 1° .

Water	79.25	Tin	14.251
Phosphorus	5.034	Bismuth	12.640
Sulphur	9.368	Lead	5.369
Sodic nitrate	62.975	Zinc	28.13
Potassic nitrate	47.371	Silver	21.07
Calcium chloride	40.7	Mercury	2.83
Sodic phosphate	66.8	Wax, unbleached	43.51

An Alloy of 3 parts bismuth, 2 lead, 2 tin . . . 4.496
 " " " 2 " " " 1 " 2 " " 4.687

125. **Facility of liquefaction proportional to the quantity of latent heat.**—The different quantities of latent heat

peculiar to different bodies, explain the different degrees of facility with which they are liquefied. Ice liquefies very slowly, because its latent heat is considerable. Phosphorus and lead, on the other hand, whose latent heat is small, melt very rapidly. Ice cannot be liquefied until it has received as much heat as would raise its own weight of water $79\cdot25$; while lead and phosphorus are liquefied by as much heat as would raise their own weight of water 5° . Hence it will be understood why it is that glaciers and vast depths of snow continue on mountain ridges, such as the Alps, in spite of the heat imparted to them during the hottest summers; such heat, however considerable, being only sufficient to liquefy a portion of their superficial strata, which descends the declivities, and feeds the streams and rivers of which they are the sources.

The circumstance of water continuing in the liquid state below its freezing point, when kept free from agitation, is not peculiar to that liquid. Tin fused in a crucible was cooled by Mr. Crichton 2° below its melting point, and yet remained liquid; and similar phenomena have been observed with other metals. In all such cases, the moment solidification commences, the liquid, as in the case of water, suddenly rises to its point of fusion; and the same causes in all cases favour solidification.

126. **Refractory bodies.**—Bodies which are difficult of fusion are called refractory bodies. Among these, one of the most remarkable is carbon or charcoal, one form of which is the precious stone called the diamond. No degree of heat, as yet attained, has reduced this substance to the liquid state; indeed, diamond being crystallised charcoal, it is probable that if the fusion of charcoal could be effected, diamonds could be fabricated. Among the most refractory bodies are the earths, such as lime, alumina, barytes, strontia, &c. Of the metals, the most refractory are iron and platinum, but both of these are fused by the oxyhydrogen blowpipe, as well as by the galvanic current.

127. **Change of volume attending change of state.**—When a liquid passes into the solid state by the absorption of heat, a sudden and considerable change of dimensions is frequently observed. This change is sometimes an increase and sometimes a diminution, and in some cases no change takes place at all. When mercury is cooled to its freezing point, which is -39° , it undergoes an instantaneous and considerable diminution of bulk as it passes into the solid state. An effect exactly the reverse takes place with water. When this liquid cools down to 0° , it passes into the solid state, and in doing so undergoes a consider-

able and irresistible expansion. So great is this expansion, and so powerful is the force with which it takes place, that large rocks are frequently burst when water collected in their crevices freezes. It is a common occurrence that glass bottles containing water, left in dressing-rooms in cold weather, in the absence of fire, are broken when the water contained in them freezes, the expansion in freezing not being yielded to by any corresponding dilatation in the glass. An experiment was made at Florence on a brass globe of considerable strength, which was filled with water, and closed by a screw. The water was frozen within the globe, by exposure to a cold below 0° , and in the process of freezing the water burst the globe. It was calculated that the force necessary to produce this effect amounted to about 28,000 lbs.

This sudden expansion of water in freezing is a phenomenon distinct from the expansion already noticed, which takes place as the temperature is lowered from 4° to 0° . The latter expansion is gradual and regular, and accompanied by a gradual and regular decrease of temperature; but, on the other hand, the expansion which takes place when water passes from the state of liquid to the state of ice is sudden and even instantaneous, and is accompanied by no change of temperature, the solid ice having the temperature of 0° , and the liquid of which it is formed having had the same temperature just before congelation.

When water is cooled below 0° without freezing, the expansion which took place from 4° to 0° is continued, and the liquid continues to dilate below 0° : when it is afterwards solidified by agitation, or by throwing in a crystal of ice, a sudden and considerable expansion takes place as already described, but this expansion is always less than would take place if it solidified at 0° , by the quantity of expansion which it suffered in cooling from 0° to the temperature at which it was solidified. It is observed that the expansion which water suffers in being solidified at 0° amounts to about one-seventh of its bulk. If it be solidified at a lower temperature, it will suffer a less expansion than this; but the expansion which it suffers in solidification under these circumstances, added to the expansion which it suffers in cooling from 0° downwards previous to solidification, will always produce a total amount equal to the expansion which it would suffer in solidifying at 0° . Hence the total expansion which water undergoes, from the temperature of greatest density (4°) until it becomes solid, is always the same, whatever be the temperature at which it passes from the liquid to the solid state.

The same observations will be likewise applicable to other liquids similarly solidified.

If a quantity of liquid phosphorus, at the temperature of 90° , be gradually cooled, it will be observed to suffer a regular contraction in its dimensions, according to the general laws observed in the cooling of bodies. When it is cooled to the temperature of about 44° , it passes into the solid state, and in doing so undergoes a sudden and considerable contraction. Oils generally undergo this sudden contraction in the process of freezing.

It may be assumed as generally true, that bodies which crystallise in freezing undergo a sudden expansion, and that bodies that do not crystallise in freezing, for the most part suffer a sudden contraction. Sulphuric acid, however, is an example of a liquid which passes from the liquid to the solid state, and *vice versa*, without any discoverable expansion or contraction. Most of the metals contract in passing from the liquid to the solid state, the exceptions being cast iron, bismuth, and antimony, all of which undergo expansion in solidifying.

It is evident that a metal which contracts in solidifying cannot be made to take the exact shape of the mould. It is for this reason that money composed of silver, gold, or copper cannot be cast, but must be stamped. Cast iron, on the contrary, as it dilates in solidifying, takes the impression of a mould with great precision, as do also certain alloys used in the arts.

The most striking instance of sudden contraction in cooling is exhibited in the case of mercury. This was first observed in the case of a thermometer, which, when exposed to a temperature about 40° below zero, was observed to fall suddenly through a considerable range of the scale, and in some cases the mercury was precipitated into the bulb. It was observed that the thermometer being exposed to a temperature lower than -40° , the mercury gradually falls until it arrives at about -38° , and that then a great and sudden contraction takes place at the moment the metal is solidified.

This contraction, however, must not be understood as indicating any real fall of temperature, as is the case with all the previous and regular contractions which take place before the solidification of the metal.

Substances which soften before they melt, and which pass by degrees from the solid to the liquid state, are mostly of organic origin, and their point of fusion is in general below the temperature of boiling water. Some of these, which are of most general utility in the arts, are the following :

Colophony begins to melt at 275° on Fahrenheit's scale.

Brown wax	"	"	140	"	"	"
White wax	"	"	150	"	"	"
Tallow	"	"	90	"	"	"
Pitch	"	"	85	"	"	"

128. **Weldable metals.**—The metals capable of being welded soften before they are fused ; and the heat at which they soften is called a *welding heat*. The metals which most readily admit of being welded are platinum and iron. At an incipient white heat (1220°) they become soft ; and, in this state, pieces of the metal may be intimately united when submitted to severe pressure, or when passed under the hammer. The metals thallium, lithium, and potassium afford further instances of this property. Palladium is also, in a minor degree, susceptible of it.

129. **Freezing mixtures.**—It may be taken as a physical law of high generality, that a solid cannot pass into the liquid state without absorbing and rendering latent a certain quantity of heat. This heat may be, and often is, supplied from some other body in contact with that which is liquefied. But if no such external supply of heat be present, and if, nevertheless, any physical agency cause the liquefaction to take place, the body thus liquefied will actually draw upon its own sensible heat. While it is liquefied, it will therefore fall in temperature to that extent which is necessary to supply its latent heat of liquefaction at the expense of its sensible heat.

To render this more clear, let us imagine a pound of ice at the temperature of 0° to be mixed with a pound of liquid having the temperature of $-79\cdot25^{\circ}$, and let this liquid be supposed to have the property of dissolving the ice. When the liquefaction is completed, the temperature of the mixture will be $-79\cdot25^{\circ}$. Now the liquid, which is here supposed to be the solvent, neither imparts heat to the ice nor abstracts heat from it. The ice, therefore, now liquefied, contains exactly as much heat as it contained before liquefaction, and no more. But, to become liquid, it was necessary that $79^{\circ}\cdot25$ of heat should be absorbed by it, and become latent in it. This $79^{\circ}\cdot25$ has therefore been transferred in the ice itself from the sensible to the latent state.

This principle has been applied extensively in scientific researches and in the arts for the production of artificial cold, the compounds thus used being called *freezing mixtures*.

In all freezing mixtures, two or more substances are combined, one or more of which are solid, and which have chemical properties, in virtue of which, when intimately mixed together,

they enter into combination, and, in combining, liquefy. The operation is so conducted, that no heat is supplied either by the vessel in which the liquefaction takes place, or from any other external source. Such being the case, it follows that the heat absorbed in the liquefaction must be supplied by the substances themselves which compose the mixture, and which must therefore suffer a depression of temperature proportional to the quantity of heat thus rendered latent.

The cold produced will be increased by reducing the temperature of the substances composing the mixture before mixing them. Thus, let A and B be the substances mixed. Before being combined, let them be reduced to 0° by immersing them in snow. Let them then be mixed, and let the latent heat of fusion be 20° . The mixture will fall to -20 , since the 20° of sensible heat will be absorbed. But if, at the moment of mixing them, their temperature had been 20° , then the temperature of the mixture would become 0° .

The substances which may be used to produce freezing mixtures on this principle are very various.

If equal weights of snow and common salt at 0° be mixed, they will liquefy, and the temperature will fall to -20° .

If 2 lbs. of crystallised chloride of lime and 1 lb. of snow be separately reduced to -20° in this liquid and then mixed, they will liquefy, and the temperature will fall to -60° .

If 4 lbs. of snow and 5 lbs. of sulphuric acid be reduced to -60° in this last mixture, and then mixed, they will liquefy, and the temperature will fall to -68° .

If a pound of snow be dissolved in about two quarts of alcohol at 0° , the mixture will fall nearly to -25° . If the same quantities of snow and alcohol, being reduced in this mixture to -25° , be then mixed, the temperature of the mixture will be reduced to -50° ; and the same process being repeated with like quantities in this second mixture, a further reduction of temperature to -68° may be produced; and so on.

130. Table of freezing mixtures.—There are a great variety of bodies which, by combination, serve for freezing mixtures. The following table has been collected from the results of the researches of Walker and Lowitz, the results being given in Fahrenheit's degrees. The substances are indicated by letters as follows :—

Water	W	Nitrate of potash . .	NP
Snow, or ice	I	„ ammonia	NA
Sulphate of ammonia .	SA	Sulphuric acid . . .	SA
„ soda	SS	Nitric acid	NA

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Chloride of ammonia .	MA	Hydrochloric acid .	HA
„ soda .	MS	Dilute . . .	d
„ lime .	ML	Crystallised . . .	c
Carbonate of soda .	CS		

The figures prefixed indicate the proportion by weight in which the ingredients are mixed. Thus, 6ss + 4MA + 2NP + 4dNA signifies a mixture of 6 cz. of sulphate of soda, 4 oz. of chloride of ammonia, 2 oz. of nitrate of potash, and 4 oz. of dilute nitric acid.

	From	To	Decrease of tempe- rature produced
5 MA + 5 NP + 16 W . . .	+ 50	+ 10	40
5 MA + 5 NP + 8 SS + 16 W . . .	+ 50	+ 4	46
1 NA + 1 W . . .	+ 50	+ 4	46
1 NA + 1 CS + 1 W . . .	+ 50	- 7	57
3 SS + 2 dNA . . .	+ 50	- 3	53
6 SS + 4 MA + 2 NP + 4 dNA . . .	+ 50	- 10	60
6 SS + 5 NA + 4 dNA . . .	+ 50	- 14	64
9 PS + 4 dNA . . .	+ 50	- 12	62
9 PS + 6 NA + 4 dNA . . .	+ 50	- 21	71
8 SS + 5 HA . . .	+ 50	0	50
5 SS + 4 dSA . . .	+ 50	+ 3	47
2 I + 1 MS . . .	x	- 5	
5 I + 2 MS + 1 MA . . .	x	- 12	
24 I + 10 MS + 5 MA + 5 NP . . .	x	- 18	
12 I + 5 MS + 5 NA . . .	x	- 25	
3 I + 2 dSA . . .	+ 32	- 23	55
8 I + 5 HA . . .	+ 32	- 27	59
7 I + 4 dNA . . .	+ 32	- 30	62
4 I + 5 ML . . .	+ 32	- 40	72
2 I + 3 cML . . .	+ 32	- 50	82
3 I + 4 NP . . .	+ 32	- 51	83
5 PS + 3 NA + 4 dNA . . .	0	- 34	34
3 I + 2 dNA . . .	0	- 46	46
8 I + 3 dSA + 3 dNA . . .	- 10	- 56	46
1 I + 1 dSA . . .	- 20	- 60	40
3 I + 4 ML . . .	+ 20	- 48	68
2 I + 3 ML . . .	- 15	- 68	53
1 I + 2 cML . . .	0	- 66	66
1 I + 3 cML . . .	- 40	- 73	33
8 I + 10 dSA . . .	- 68	- 91	23

The following table gives results of freezing mixtures frequently used, the materials being very handy for producing required reductions of temperature.

Materials		Proportions by Weight	Fall of temperature in Centigrade degrees
1.	{ Snow, or powdered ice	2	} From 0° to -21°
	{ Bay-salt	1	
2.	{ Snow	3	} From 0° to -48°
	{ Crystallised calcium chloride	4	
3.	{ Nitrate of ammonia	1	} From $+10^{\circ}$ to -15°
	{ Water	1	
	{ Sal-ammoniac	5	
4.	{ Nitrate of potash	5	} From $+10^{\circ}$ to -15°
	{ Sulphate of soda	8	
	{ Water	16	
5.	{ Sulphate of soda	8	} From $+10^{\circ}$ to -17°
	{ Hydrochloric acid	5	

Thioliér produced a powerful freezing mixture, by solidifying carbonic acid, and mixing it with sulphuric acid or sulphuric ether. A temperature 120° below zero, and therefore 152° below the freezing point, was thus produced.

Mitchel, repeating the experiment, produced a still more intense cold. He exposed alcohol of the specific gravity of 0.798 successively to the temperature of -90° and -100° . He states that at the former temperature it had the consistency of oil, and at the latter resembled melting wax.

If these experiments can be relied on, it may be inferred that the freezing point of alcohol, so long and hitherto so vainly sought, is probably about -102° , or about 102° below the freezing point of water and 60 degrees below that of mercury.

To ensure success in experiments on extreme cold produced by freezing mixtures, the salts used must not have lost their water of crystallisation, because in that case they quickly absorb water, and converting it into ice liberate heat and obstruct the cooling. The salts and ice used should be pulverised so as to dissolve quickly. When extreme cold is required, the vessel containing the freezing mixture should be immersed in another vessel, containing also a freezing mixture, so as to prevent the mixture under experiment from receiving heat from the vessel which contains it, and a sufficient quantity of the ingredients forming the freezing mixture should be used.

The greatest natural cold of which any record has been kept was that observed by Professor Hansteen between Krasnojarsk and Nishne-Udmiks in 55° N. lat., which he states amounted to -55° (Reaum. ?) = -98.75° F.

At Jakutsk, the mean temperature of December is $-44\frac{1}{2}^{\circ}$ F. In 1828, from January 1 to January 10, the mean temperature of that place was -58° .

In the expedition to Khiva, in December 1839, the Russian army experienced for several successive days a temperature of $-41^{\circ}\cdot 8$ F.

131. **Apparatus for producing artificial cold.**—The most simple apparatus for using a freezing mixture, and lowering by means of it the temperature of water or any given substance, is represented in *fig. 42*, and is composed of a tin bucket $A B C D$, having a slightly conical form, in the bottom of which is a circular hole, a little less in diameter than the bottom. In this hole is soldered the mouth of another tin bucket, $G E F H$, also conical, but with its smaller end upwards. A space w is thus left between the two tin buckets, in which the water or other substance to be cooled is placed.

The freezing mixture is placed in another vessel, $I K L M$, (*fig. 43*), similar in form to the bucket $A B C D$. This vessel

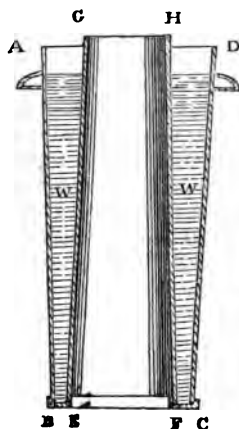


Fig. 42.

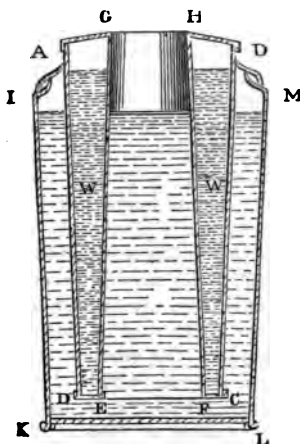


Fig. 43.

$I K L M$ ought to be made of some non-conducting material. Common glazed earthenware would answer the purpose. When the freezing mixture is placed in it, the vessel $A B C D$ is immersed in it; so that the cold liquid is not only in contact with the external surface of the tin bucket $A B C D$, but also with the inner surface of $G E F H$. The water w , or whatever other sub-

stance it is required to cool, is therefore quickly reduced in temperature.

If it be not convenient to provide a vessel such as *I K L M* in earthenware, a tin vessel thickly coated with woollen cloth may be used.

The freezing apparatus of M. Carré consists essentially of two vessels made of strong galvanised iron plate, and connected by means of a metal tube. One of the vessels, which we may call *A*, is a cylindrical boiler, three parts filled with a strong solution of ammonia. The other vessel, *B*, called the *freezer*, is slightly conical, and consists of two concentric envelopes, in such a manner that its centre being hollow, a metal vessel containing the water to be frozen can be placed in this space. Thus only the annular space between the sides of the freezer is in communication with the boiler by means of the metal tube. The process of freezing comprehends two distinct operations. First, the boiler being placed over a fire, the freezer into a cold water bath; the ammoniacal gas dissolved in the water is disengaged, and in virtue of its own pressure is liquefied in the freezer along with a comparatively small amount of water. When the thermometer inserted in the boiler indicates a temperature of about 130° , the distillation of *A* towards *B* is stopped, and the second operation begins. This consists in placing now the boiler in the cold water bath and the freezer outside, care being taken to wrap round it some dry flannel. The vessel containing the water to be frozen is also now immediately placed inside the freezer. As the boiler cools, the ammoniacal gas with which it is filled is again dissolved, and the pressure thus decreasing rapidly within the boiler, the ammoniacal gas which has been liquefied in the freezer assumes as rapidly the gaseous form, and passes from the freezer to the boiler, to be re-dissolved in the water remaining in the latter. During this passage from the liquid to the gaseous state the ammonia absorbs a great quantity of heat, which is withdrawn from the water in the vessel placed into the freezer, hence this water freezes.

132. **Action of fluxes.**—The same principle which explains the effect of freezing mixtures, connected with the fact that alloys and mixtures have in general a lower fusing point than the component substances, is also applicable to the phenomena attending fluxes in metallurgy. *Fluxes* are certain bodies which, when mixed with others, cause them to fuse at lower temperatures than their proper point of fusion. It is by this means that certain metals and metallic ores are fused, when exposed to the operation of blast furnaces. In a certain sense

salt may be said to be a flux for ice ; but this term flux is usually limited in its application to bodies which are only fused at very elevated temperatures : for example, in enamelling, and in the manufacture of glass and of the paste by which precious stones are imitated, siliceous sand is employed in greater or less proportion, about one-third for enamel, and nearly three-fourths for plate glass. Now silica is not fused at any heat attainable by common furnaces. M. Gaudin was the first to succeed in its fusion, by means of the oxy-hydrogen blow-pipe, and drew it into threads as fine as filaments of silk. When combined, however, with proper fluxes, it fuses readily in the furnace. The fluxes used vary according to the purposes for which the silica is applied, but they consist generally of soda, potash, and lime, with the addition of lead for flint glass, and stannic acid for enamel. The compound which results from the mixture of these ingredients, by their exposure to intense heat, is reduced to a sort of pasty fusion, but can never be said to undergo positive liquefaction. Nevertheless, the beautiful transparency of Bohemian glass, plate glass, flint glass, and the artificial diamonds, show that the constituents must be combined in a very intimate manner.

Fine earthenware and porcelain are also fabricated by means of fluxes ; in these cases fusion is not actually produced, nor is there the same intimate combination of the constituents as takes place in vitrefaction, still there is a partial combination, and an incipient fusion. The fluxes consist here also of soda, potash, lime, and sometimes magnesia ; the soda and potash, however, being used in their combined form of feldspar.

133. Various experimental facts and practical consequences.—Infusible bodies may be resolved into two classes, those which are refractory, and which alone can be properly said to be infusible, and those whose fusion is prevented by their previous chemical decomposition or composition. Before the invention of the oxy-hydrogen blow-pipe, and other scientific expedients for the production of intense heat, the number of refractory substances was much more considerable than it is at present. Scarcely any body can be said to be absolutely infusible except charcoal, which, under all its forms of pure carbon, anthracite, graphite, and diamond, has resisted fusion at the highest temperature which has yet been produced.

The term refractory, however, is still applied to those classes of substances which resist fusion by ordinary furnaces.

When certain compound bodies are exposed to an intense heat, they are resolved into their constituents before they attain

the point of fusion ; and in other cases simple bodies enter into chemical combination with others which surround them, or are in contact with them before the fusion takes place.

The fusion, however, may in some cases of both of these classes of bodies be effected by confining them in some envelope which will resist the separation of their constituents if they be compound, or exclude them from contact with bodies with which they might combine if they be simple.

If marble be exposed under ordinary circumstances to an intense heat it will be resolved into its constituents, lime and carbonic acid ; but if it be confined in a strong gun-barrel, for example, it may be fused.

Almost all organic solids, except the resins and the fats, are infusible before they are decomposed ; we cannot melt a piece of wood, a leaf, a flower, or a fruit ; but after having evaporated their liquid constituents, and dried them, the influence of heat causes their constituents to enter into new combinations, producing new substances which are generally volatile, and which have nothing in common with the original substances.

When water holding any substance in solution has its temperature sufficiently lowered, its congelation takes place in one or other of three ways ; first, the water may congeal independently of the body which holds it in solution ; secondly, the body which it holds in solution may congeal, leaving the water still liquid ; thirdly, the water and the body it holds in solution may congeal together.

The congelation of the water independent of the substance it holds in solution is presented in the case of the very weak solutions. In this case, the point of congelation is always below the freezing point. Thus, if water holds in solution a small quantity of alcohol, acid, alkali, or salt, it will be necessary to reduce the whole to below the freezing point of water to produce its congelation ; but when ice has been formed, this ice will consist of pure water, without the mixture of any portion of the substances which the water held in solution. Thus, sea-water freezes at about three degrees below the freezing point of pure water ; and if the ice produced in it be withdrawn and melted, it will produce pure water. In the same manner, if weak wine be frozen, the ice formed upon it will be the ice of pure water, and the wine which still remains liquid will be proportionally stronger. This method is sometimes practised to give increased strength to wine.

Water is generally capable of holding in solution only a certain quantity of any solid substance, and when all the substance

has been dissolved in it which it is capable of taking, the solution is called a saturated solution. Now, it is found that the quantity of solid matter of any kind which water is capable of holding in solution, in general increases with the temperature. Thus, water at 100° will hold more of a given salt in solution than would water at 50° . Let us suppose, then, that a saturated solution of any salt is made at 90° . If this solution be allowed to cool, a part of the salt which it retains must return to the solid state, since at lower temperatures it cannot hold in solution the same quantity; and in proportion as the temperature of the solution falls, the quantity of solid matter which will be formed in it will increase. In this case, the cooling produces a change in the composition of the solution. If the cooling be accomplished suddenly, the salt is precipitated tumultuously and in a confused mass, without form or cohesion; but if the solution is allowed to cool slowly and without agitation, the molecules of the salt collect into regular crystals.

Even after the temperature of the solution has ceased to fall, the decomposition and crystallisation will continue, if the vessel containing the solution be in a position favourable to superficial evaporation. The water which evaporates from the surface taking with it none of the salt, all that portion of salt with which it was combined will receive the solid form, and will collect into crystals; and this process may be continued until, by superficial evaporation, all the water shall have disappeared, and nothing be left in the vessel except a collection of crystals of the salt.

The solution of anhydrous sulphate of soda presents some remarkable exceptional phenomena. At the temperature of $17^{\circ}9$ it has a maximum of saturation; that is to say, above this point, as well as below it, the proportion of salt which it contains diminishes. However, at the boiling point, it contains much more salt than at the common temperature. If the solution be boiled in a large tube, and when it is well purged of air the tube be closed at the top, so as to exclude the atmosphere, the cooling will take place without any solidification; but when the top of the tube is broken so as to admit the air, the salt is suddenly congealed in a mass, with so great a disengagement of heat that the tube becomes warm to the touch. Again, if a solution saturated at $17^{\circ}9$ be simply heated to boiling, without allowing any loss of liquid by evaporation, it will deposit in crystals more than one fifth of the salt which it previously held in solution.

In some cases the water and the salt which it holds in solu-

tion are solidified together. This happens when the salts contain water of crystallisation. The phenomena are produced in the same manner as in the case just described, with this difference, that the molecules of salt, in collecting, carry with them the molecules of the water of crystallisation, which pass also to

the solid state, taking the place which belongs to them in the crystals. Nevertheless, the solidification of the water disengaging in general much more latent heat than the solidification of the salt, the crystals undergo a less rapid increase, whether formed by mere cooling, or by evaporation of a part of the dissolving mass.



Fig. 44.

134. **Dutch tears.**—When bodies liquefied by heat are suddenly cooled, some remarkable and exceptional phenomena are often produced. Thus, if large drops of glass in a state of fusion be let fall into a vessel of cold water, the solidification of their superficial parts is immediate; that of their interior is much more slow.

There results from this a sort of forced and unnatural arrangement of the molecules of the drop, which explains the singular phenomenon produced by Dutch Tears, so called from the form they assume, as represented in *fig. 44*. If the extremity of the tail of one of these be broken, in an instant the entire mass cracks, and is reduced to powder. This arises from the fact that, the glass not being cooled slowly and gradually, the molecules in solidifying have not had time to assume their natural position, and, being in a forced position, on the least disturbance separate.

135. **Annealing and tempering.**—To prevent such constraint in the molecules, articles manufactured of glass, for example, are submitted to the process called annealing, after their fabrication; a process in which, being again raised to a certain temperature, after being shaped, they are allowed to cool very slowly. Pottery in general is submitted to the same process.

The tempering of steel is analogous to this. Steel heated almost to the point of fusion, and then plunged in water, becomes as brittle as glass. In this state it is said to have the highest temper. This extreme hardness and brittleness may be removed by the process of tempering, which consists in heating the steel moderately, and then allowing it to cool. The tempering of steel is an operation of great practical importance, as from the variety of purposes to which it is applied, it is required of very different degrees of hardness, and upon the due adjustment of this quality much of its utility depends. The degree to which the temperature is raised in the process of

heating regulates this point ; the higher the heat the softer is the steel. If it is tempered only at a cherry red, it is less hard and less brittle. This is what is called the ordinary temper. In short, it may be tempered in an infinite variety of degrees over a fire of small charcoal, according to the temper which it is desired to impart to it. The oxydation which it suffers at the surface indicates, by the colour which it gives to it, the degree of tempering which it has received. Thus, it sometimes acquires a blue colour, and sometimes a straw colour ; the latter colour indicating a harder and less elastic quality.

136. **Retardation of Solidification.**—Liquids may be cooled, under particular circumstances, below the melting point of the corresponding solid body without solidifying. This phenomenon, to which the name *retardation of solidification* has been given, occurs especially when the liquid is cooled very slowly, and is at the same time protected from all mechanical disturbance. Water, for example, when kept at perfect rest, and under a pressure somewhat greater than that of the atmosphere, may be cooled to -15° without freezing. But when water is at that temperature, the slightest agitation or contact with a solid body is mostly sufficient to cause solidification of a portion of the mass. The smaller the quantity of liquid operated upon the lower is the temperature to which it can be cooled, and the greater the mechanical disturbance which it will support without freezing. Mists occur frequently, which are formed by particles of liquid water suspended in an atmosphere of which the temperature was 10, 12, or even 15 degrees below zero. Again, in capillary tubes the freezing of water is considerably retarded. *Sorby* and *Despretz* found that in glass tubes of one-tenth of a millimetre in diameter, water could be maintained in the liquid state as low as from -17° to -20° . It is probably due to this cause that the sap is not oftener frozen in the capillary vessels of plants.

Dufour observed remarkable phenomena of this kind in the case of liquids cooled without contact with any solid body. He suspended globules of the liquid under examination in some other liquid of the same specific gravity, but of lower freezing point, and in which it was insoluble. Thus water was examined while suspended in a mixture of chloroform and sweet oil of almonds ; sulphur and phosphorus in an aqueous solution of chloride of zinc and naphthalene in water. In the experiments with water, the spheres of this liquid which floated in the mixture of chloroform and oil were very rarely seen to freeze at 0° ; in general, solidification occurred between -4° and -12° ,

the smaller globules, as a rule, remaining liquid to a lower temperature than the larger ones, some of them having been repeatedly seen still liquid at -18° or -20° . Agitation and the contact of solid bodies appear to have much less effect in causing the solidification of liquids cooled in this way than when they are cooled to the same extent in glass vessels. Dufour found that the globules of water in his experiments often did not solidify when displaced or violently deformed by a glass rod, and even that crystals of chloride of sodium, sulphate or nitrate of potassium, sugar, etc., would sometimes fall *through* a globule of water 5 millimetres in diameter, and cooled to at least -8° , without producing any effect. Contact with a fragment of *ice*, however, invariably caused immediate congelation.

Dufour obtained globules of sulphur (melting point 115°) of 6 millimetres diameter still liquid at 40° , and globules of 0.5 millimetre diameter remained liquid for several days at 5° or 10° . Globules of phosphorus (melting point 45°) of considerable size were cooled to 20° , and globules of 1 or 2 millimetres diameter to 0° without solidifying. Globules of naphthalene (melting point 79°) were obtained still liquid at 40° .

When a liquid solidifies after having been thus cooled below its normal freezing point, the solidification takes place very rapidly, and is accompanied by a disengagement of heat, often sufficient to raise its temperature from the point at which solidification begins up to its ordinary freezing point. This is well seen with crystallised hyposulphite of sodium, which melts in its water of crystallisation at 45° , but when carefully cooled will remain liquid for a long time at the temperature of the atmosphere. If it be then caused to solidify, by agitation, or by throwing in a small fragment of the solid salt, the resulting rise of temperature is such as to be distinctly felt by the hand.

This phenomenon of continued liquidity is seldom observed in so marked a degree as in the above instances, but, on the other hand, it occurs so frequently to a less extent, that, when the temperature of transition from the solid to the liquid state or *vice versâ* is to be used as a mark of the chemical identity of the substance, it is much safer to determine the melting point than the freezing point, for the former temperature is not subject to variations of the same kind.

137. Change of Volume accompanying Fusion and Solidification.—The change of volume, which accompanies the change of the solid state into the liquid, and *vice versâ*, has

already been described with reference to several substances. Most solids have an accelerated rate of expansion as they approach their melting points, and this is in most cases followed by a further expansion during the actual process of liquefaction, so that the melted substance occupies a greater bulk than the solid of the same temperature from which it is formed. This phenomenon has been particularly studied by *Kopp*, who obtained results of great interest. Yellow phosphorus (specific gravity at $10^{\circ} = 1.826$) expands uniformly up to its melting point (about 44°), at which temperature its volume is 1.017, that at 0° being unity; but when melted its volume at the same temperature is 1.052 of the volume at 0° . It follows that 100 volumes solid phosphorus at 44° become 103.4 volumes liquid phosphorus at the same temperature. Sulphur (native crystals, specific gravity 2.069) expands irregularly near its melting point (115°). Its volume being 1 at 0° is 1.010 at 50° ; 1.037 at 100° ; 1.096 at 115° ; at the moment of fusion the expansion amounts to 5 per cent., the volume then increasing to 1.150. Wax (bleached bee's-wax, specific gravity 0.976 at 10°) expands very rapidly as it approaches its melting point (64°), but only 0.4 per cent. more at the moment of fusion. If the volume at 0° is 1, the volume at 50° is 1.068; at 60° is 1.128, at 64° is 1.161, and increases by fusion to 1.166. Stearic Acid (pure, specific gravity nearly 1.0 at 10°) expands less than wax before melting, but then expands as much as 11.0 per cent. The volume at 0° being 1, it is 1.038 at 50° , 1.055 at 60° , and 1.079 at 70° , at which temperature the acid melts, its volume increasing to 1.198. Rose's fusible metal (2 parts bismuth, 1 part tin, and 1 part lead; specific gravity 8.906 at 10°) expands when heated from 0° to 59° in the ratio of 1 to 1.0027; but contracts when further heated, its volume at 82° being equal to that at 0° , and at 95° equal to 0.9947; in melting, between 95° and 98° , it expands by 1.55 per cent., so that at 98° its volume is equal to 1.0101. This alloy, therefore, contracts from 59° up to its melting point. Water presents a remarkable exception to the general rule, and expands at the moment of solidification; that is, ice contracts on melting by about 10 per cent. One volume of ice at 0° gives 0.908 volume of water at the same temperature, or 1 volume of water at 0° gives 1.102 volume of ice. Dufour found, as the mean of twenty-four experiments, the density of ice at 0° equal to 0.9175, that of water at the same temperature being 1. Brunner found for the density of ice the number 0.918, and Bunsen, who determined it in con-

nection with his ice-calorimeter, found it to be in the mean 0.91674 .

The expansion of water at the moment of its solidification is intimately connected with the fact, stated in the next paragraph that increase of pressure retards the freezing of water instead of facilitating it, as it does that of most other liquids ; and it enables us to understand the phenomenon. It has been shown in Article 70 that heat applied to a bulk of water at 0° diminishes this bulk up to a temperature of 4° . It is clear that pressure applied to a bulk of water at 0° will also tend to diminish the bulk, and will thus oppose the change of volume which occurs on freezing. Since, therefore, both heat and pressure act in the same sense, it is easily conceivable that, within certain limits at least, one agent may replace the other, and that a strong pressure applied to water at or below 0° may as effectually prevent its solidification as the communication of heat, which would raise its temperature above the freezing point. In the case of substances whose volume in the solid state is less than their volume in the liquid state pressure acts in the opposite sense to heat, and therefore retards liquefaction and promotes solidification.

138. **Influence of Pressure upon the Temperature of Fusion.**—The melting points of solids or freezing points of liquids are not perceptibly affected by the ordinary variations of atmospheric pressure ; but greater differences of pressure produce very sensible effects. Sir *W. Thomson* was the first to observe that pressures of 8.1 and 16.8 atmospheres caused a lowering of the melting point of ice to the extent of 0.059 and 0.129 respectively. By a still greater pressure *Mousson* succeeded in maintaining water in the liquid state at 5 degrees below zero, and by a pressure estimated at $13,000$ atmospheres he caused ice to melt at -18° . The following results are due to *Hopkins*, who experimented on spermaceti, wax, sulphur, and stearin.

Pressure	Melting point of			
Atmospheres	Spermaceti	Wax	Sulphur	Stearin
1	51.1	64.7	107.2	67.2
520	60.0	74.7	135.2	68.3
793	80.2	80.2	140.5	73.8

Bunsen experimented on spermaceti and paraffin with the following results :

Spermaceti		Paraffin	
Pressure	Freezing point	Pressure	Freezing point
Atmospheres	°	Atmospheres	°
1	47·7	1	46·3
29	48·3	85	48·9
96	49·7	100	49·9
141	50·5		
156	50·9		

It will thus be seen that in the case of substances like those experimented on by *Hopkins* and *Bunsen*, the specific gravity of which is greater in the solid than in the liquid state, the point of fusion is raised by increase of pressure.

These phenomena will be further considered in the chapter on the dynamical theory of heat.

139. **Regelation.**—This name is given to the phenomenon that pieces of moist ice placed in contact with one another will freeze together even in a warm atmosphere. The most obvious explanation of the fact rests on the principles just explained. At the boundaries of the film of water which connects the pieces placed in contact capillary action, takes place, which produces an effect equivalent to attraction, just as two plates of clean glass with a film of water between them tend to adhere. Ice being wetted by water, the boundary of the connecting film is concave (see **HYDROSTATICS** in this series, Article 77, page 105), and this concavity implies a diminution of pressure in the interior. The film, therefore, exerts upon the ice a pressure less than the atmosphere, while the remote sides of the blocks are exposed to atmospheric pressure. As a consequence a definite pressure is exerted upon the small surface of contact, and there the melting point is lowered. Melting of ice therefore occurs at the places of contact, accompanied by absorption of heat, hence the adjacent portion of the water film freezes, its freezing point being a little above the ordinary freezing point, because the film is at a less than atmospheric pressure.

CHAPTER VIII.

VAPORISATION AND CONDENSATION.

140. **Evaporation in free air.**—If a liquid be exposed in an open vessel, it will be gradually converted into vapour, which, mixing with the atmosphere, will be dissipated, and after a certain time the liquid will disappear. This phenomenon, called evaporation, was formerly explained by the supposition that the air had a certain affinity for the liquid in virtue of which the air *dissolved* it, just as water dissolves sugar or salt.

A conclusive proof against the truth of this hypothesis is presented by the fact that the vaporisation of a liquid takes place in a vacuum, and that the presence of air not only does not cause more of the liquid to be evaporated than would have been evaporated in its absence, but actually retards and obstructs the evaporation.

To be enabled to examine and observe with clearness and precision the mechanical properties of the vapour of any liquid, it is necessary to provide means by which such vapour can be separated from air and all other gases and vapours, since, being mixed with these, its properties would be modified, so that it would be difficult to determine what effects are due to the vapour, and what to the gases with which it is combined.

This object may be attained by the following apparatus, the principle of which we shall now explain.

Let $A B$ (*fig. 45*) be a glass bulb and tube, the bore of the tube being very small compared with the capacity of the bulb. Let the tube be widened into a sort of bell-shaped mouth at the end B , and let a graduated scale be engraved upon it, the zero being near the bulb.

Let the tube, held with the open end B upwards, be filled with pure mercury well freed of air, as described in the volume on HYDROSTATICS, in this series, page 135. Placing the finger on B to prevent the escape of the mercury or the entrance of air, let the tube be inverted, and the end B immersed in a trough of mercury, as represented in *fig. 46*. If it be immersed to such a depth that the height of the top of the bulb A above the level $L L'$ of the mercury in the trough is less than the height of the barometric column, the mercury will not fall from the bulb, being sustained there by the atmospheric pressure.

But if the bulb be raised to a greater height A' above $L L'$, the column of mercury will not rise with it, but will stand at the height of the barometric column.

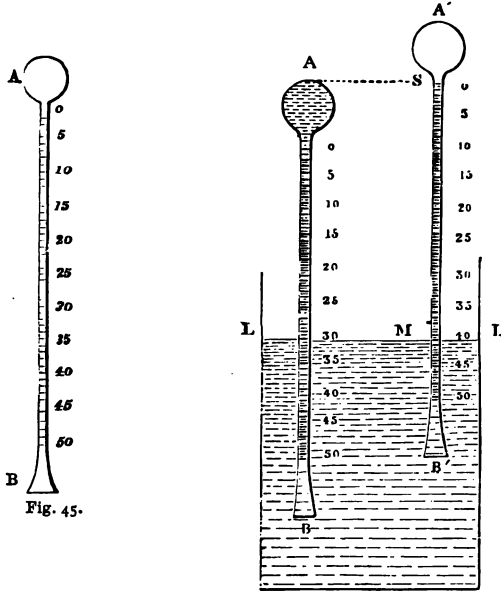


Fig. 45.

Fig. 46.

Let the bulb be raised to such a height A' that the zero of the scale engraved on the tube shall be at a height above $L L'$ equal to the barometric column. In that case the level of the column of mercury in the tube will coincide with the zero of the scale, and the space in the bulb and tube above this level will be a vacuum. Let this space be $s A'$, and let $s M$ represent the column of mercury which corresponds in height with the barometer.

Let $C D$ (fig. 47) be a small iron cylinder containing mercury, above which is a piston by which it can be pressed downwards. This piston is urged by a screw, so as to be capable of being moved with accuracy through any proposed space, how-

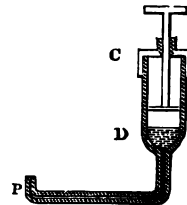


Fig. 47.

ever small. Attached to the bottom of the cylinder *c d* is a very fine tube *d p*, bent into a rectangular form so as to present its mouth upwards. This capillary tube is filled with the liquid the vapour of which it is desired to submit to observation. By means of the screw acting on the piston, any proposed quantity of this liquid can be expelled from the mouth *p* of the tube.

This instrument being immersed in the trough *l l'* (*fig. 46*), and the mouth of the tube *p* being directed into the bell-shaped end of the tube *b*, a certain small quantity of the liquid is expelled by means of the screw, and issues from *p*. Being less heavy than mercury it rises through the latter, and arrives at the top *s* of the column. There it *instantly disappears*, and at the same time the mercury falls to a lower level.

141. Vapour of a liquid an elastic fluid like air.—The cause of this will be easily understood. The minute drop of liquid which rises to the surface is converted into vapour on arriving there, and is diffused in that state throughout a certain portion of the entire capacity of the tube and bulb. It is in general transparent and invisible like air; and, therefore, notwithstanding its pressure, the bulb and tube appear to be empty, as they would if they were filled with air.

142. How its pressure is indicated and measured.—But this vapour being, like air, exercises a certain pressure upon the mercurial column *s m*, which pressure is manifested and measured by the fall of that column. The summit, which before stood at the zero of the scale, now stands at a lower point, and the number of the scale indicating its position, expresses the pressure of the vapour in inches of mercury. Thus, if the summit *s* of the column stand at half an inch below zero, the pressure of the vapour in the bulb is such as would support a column of mercury half an inch in height.

Now let us suppose another small drop of the liquid to be injected by the apparatus *fig. 47*. Like effects will ensue, and the summit *s* of the column will fall still lower, showing that the pressure of the vapour is augmented.

143. Saturated space.—By repeating this process, it will be found, that when a certain quantity of the liquid has been injected, no more vapour will be produced, and the liquid will float on the summit *s* of the mercurial column without being vaporised. The summit of the column will not be further depressed.

It appears, therefore, that the space in the bulb and tube is then *saturated* with vapour. It has received all that it is capable of containing. That this is the case will be rendered manifest by elevating the tube. The summit *s* of the column still main-

taining its height above $L L'$, a greater space will be obtained above s , and it will be accordingly found that a portion of the liquid which previously floated on s is vaporised ; and if the tube be still more elevated, the whole will disappear.

Since during this process the height $s m$ of the mercurial column in the tube remains unaltered, it follows that the pressure of the vapour remains the same.

By comparing the volume of the liquid ejected from r , *fig.* 47, with the volume of the tube and bulb filled by the vapour into which it is converted, the density of the vapour, or, what is the same, the volume of vapour into which one unit of volume of the liquid is converted may be ascertained.

There are, however, other circumstances connected with this process, which are not rendered apparent, and which it is important to observe and comprehend.

When the liquid rises to the surface of the mercurial column and becomes vapour, it absorbs a certain quantity of heat which becomes latent in it. This heat must be supplied by the tube, the bulb, and the mercury ; and as the temperature of these does not permanently fall, this heat is replaced, and their temperature restored by the surrounding air. The quantity of heat absorbed in the evaporation of the liquid will be presently shown. Meanwhile it must be observed that the supply of the latent heat is essential to the evaporation of the liquid. If the mercury on which the liquid floats, and the glass by which it is inclosed, were absolute non-conductors, and could impart no heat whatever to the liquid, then the evaporation could not take place.

It appears from what has been explained, that when the space above the mercury has been charged with a certain quantity of liquid in the state of vapour, or, what is the same, when the vapour it contains has attained a certain density, all further evaporation ceases ; and any liquid which may be injected will remain in the liquid state, floating on the mercury. So long as the temperature of the surrounding medium, and consequently that of the bulb and its contents, remains unaltered, and so long as any liquid remains floating on the mercury, the pressure and the density of the vapour in the bulb will be unaltered. If the bulb be raised, so as to give more space for the vapour, a proportionally increased quantity of the liquid will be vaporised ; and if by depressing the tube the volume of the vapour be diminished, a corresponding part of it will return to the liquid state. In the one case, heat will be absorbed by the liquid evaporated ; and in the other, heat will be given out by the vapour con-

densed. This heat is borrowed from the surrounding atmosphere in the former case, and imparted to it in the latter ; since, otherwise, the bulb and its contents must undergo a change of temperature, contrary to what was supposed.

144. Quantity of vapour in saturated space depends on temperature.—But let us now consider what will be the effect of raising or lowering the temperature of the bulb and its contents. The bulb being charged with vapour, and a stratum of unevaporated liquid floating on the mercury, let the temperature of the medium surrounding the bulb be raised through any proposed number of degrees of the thermometric scale. This will be immediately followed by the evaporation of a part of the liquid floating on the mercury, and a depression of the column. An increased volume of vapour is therefore now contained in the bulb and tube ; but if this increase of volume be compared with the increased quantity of liquid evaporated, it will be found to be less in proportion ; and it consequently follows that the density of the vapour is augmented ; and since the column of mercury has been more depressed, and since this depression measures the pressure of the vapour, it follows that this pressure has been also augmented.

145. Relation between pressure, temperature, and density.—Thus it appears that the pressure and density of the vapour produced from the liquid floating on the mercury are augmented as the temperature of the liquid is augmented, and consequently diminished as that temperature is diminished.

In short, a certain relation subsists between the temperature, pressure, and density, such that when any one of these are known, the other two can always be found. If this general relation were known, and could be expressed by an arithmetical formula, the pressure and density of the vapour corresponding to any proposed temperature, or the temperature corresponding to any proposed density and pressure, could always be ascertained by calculation. But the theory of heat has not supplied the means of determining this relation by any general principles ; and, consequently, the pressures and densities of the vapour of liquids at various temperatures have been determined only by experiment and observation.

146. Vapours of different Liquids.—Different liquids at the same temperature produce vapours having different pressures and densities. A form of apparatus adapted to illustrate this experimentally is shown in *fig. 48*.

A series of glass tubes being filled with mercury and inverted in a cistern of that liquid, by the process already described in

One of the tubes being reserved as a barometric standard, a drop of each of the liquids to be examined is let into the others, when it will be observed that the moment the bubble of the liquid rises to the summit of the mercurial column, that column will instantly fall, and it will fall to different points in the several tubes, showing that at the same temperature the vapours of different liquids produced in a vacuum will have different pressures.

It is necessary to observe, however, that in the performance of this experiment a sufficient quantity of liquid must be introduced into each of the tubes to leave more or less of it unevaporated at the summit of the mercury, since otherwise the vacuum above the mercury would not be saturated with vapour.

147. Experiments on the relation between pressure, temperature, and tension of vapour of water.—Of all liquids, that of which the vaporisation is of the greatest practical importance, and consequently that which has been the subject of the most extensive system of observations, is water.

If water be introduced above the mercurial column in the apparatus above described, and be exposed successively to various temperatures, the pressures and densities of the vapour it produces can be observed and ascertained.

It is thus found that, in all cases, water passing into the vaporous state undergoes an enormous enlargement of volume, and that this enlargement increases as the temperature at which the evaporation takes place is diminished. Thus, if the temperature be that of the boiling point, viz. 100° , a cubic inch of water swells into 1696 cubic inches of vapour at the same temperature, the pressure upon the vapour being that of the atmosphere.

148. Water evaporates at all temperatures.—There is no temperature, however low, at which water will not evaporate. If the bulb and tube be exposed to the temperature of 0° , the mercurial column in the tube will be lower than the barometric column by two-tenths of an inch—a small but still observable quantity; and even if the temperature be reduced still lower, so that the liquid floating on the mercury shall become solid ice, there will still be a vapour in the bulb of appreciable pressure and density. Thus, a piece of ice at the temperature of -2° produces a vapour whose pressure is represented by a column of mercury of a twentieth of an inch.

149. The apparatus of Gay Lussac.—This apparatus for determining the pressure of the vapour of water below the freez-

ing point consisted of two barometric tubes, filled with mercury, and inverted in the usual manner in a cistern of that fluid, as shown in *fig. 49*. One of these, *A*, was used as a barometer, and the other, being curved at *c*, had its extremity immersed in a vessel containing a freezing mixture, in which was also plunged a thermometer, *t*, to show its temperature. A drop of water

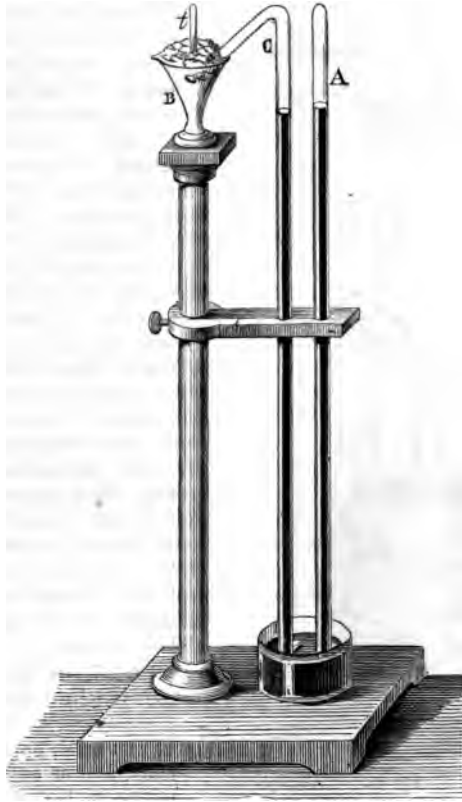


Fig. 49.

being then let in at the lower end of the bent tube in the usual way, the mercury in that tube will fall below its level in the tube *A*, by a quantity which will vary with the temperature of the freezing mixture in *B*.

160. GENERAL EFFECTS OF HEAT UPON BODIES.

This depression of the mercurial column in the tube c is produced by the pressure of the vapour evolved from the water which floats on the mercury in that tube. But this water is evidently not exposed to the same temperature as that part of its vapour which is enveloped in the freezing mixture, and it

might therefore be supposed that the pressure indicated by the difference of the columns in the two tubes might be as well taken to be that corresponding to the water in the tube c, as that which would correspond to the temperature of the freezing mixture. But it will presently appear that when the vapour of a liquid communicates freely between two vessels, the temperature of one of which is lower than that of the other, the pressure of the vapour will correspond to the lower temperature.



Fig. 50.

150. Dalton's apparatus.—The apparatus (*fig. 50*) with which Dalton ascertained the pressure of the vapour of water between 0° and 100° , consisted of two barometric tubes A and B, filled and inverted as usual, and plunged in a cistern F of mercury. A cylindrical glass vessel, open at both ends, and of sufficient capacity to include the two

tubes, surrounds them, and is also immersed in the mercury. This vessel is filled with water to a level above the tops of the tubes, and a thermometer D C, let into it, is supported above it; a charcoal furnace is placed under the mercurial cistern F, and a divided scale E, is placed beside the apparatus to indi-

cate the heights of the column. Water is then let into one of the tubes B, the other A being reserved as a barometer, and the temperature of the mercury in F, and therefore of the water which rests upon it, being gradually elevated, the mercury in B will fall lower and lower, according as the temperature rises, and the difference between the columns in A and B, corresponding to each temperature, will give the measure of the pressure of the vapour. At the temperature of about 100° the mercury in the vapour-barometer falls to the level of the cistern, and the method is therefore inapplicable for higher temperatures.

Dalton's method has two essential defects. In the first place, it is impossible to ensure that the temperature shall be everywhere the same in a column so long as that which is formed by the vapour when the temperature becomes 70° and more. In the second place, there is the disadvantage of having to observe the difference of level through the sides of a cylindrical vessel, which must introduce a certain amount of uncertainty.

Regnault, who used Dalton's apparatus up to temperatures of 50° C., improved the apparatus so as to free it as far as possible from the stated objections. At such low temperatures the tension of the vapour is never more than 4 inches, and it becomes unnecessary to heat the barometers throughout their entire length. The two barometers traverse two holes in the bottom of a metal box. In one of the sides of the box is a large opening closed with plate glass, through which the necessary observations can be made with great accuracy. The liquid column being short, it becomes very easy, by bringing a spirit-lamp within different distances of the box, to maintain for a sufficient time any temperature between 0° and 50° C.

151. **Arago and Dulong's apparatus.**—The pressure of steam proceeding from water at temperatures above the boiling point was ascertained experimentally by Messrs. Arago and Dulong, and also by M. Regnault. The apparatus used by the former consisted of two gun barrels, closed at their lower ends, and inserted steam-tight in a boiler; each of these barrels was filled with mercury, and contained a thermometer which showed the temperature, the one of the water, and the other of the steam in the boiler. To measure the pressure of the steam, a syphon gauge, similar in principle to the tube for demonstrating Mariotte's law (see HYDROSTATICS, page 156), was used. In this way, the pressure of steam from one to twenty-four atmospheres, with its corresponding temperature, was ascertained.

152. **Regnault's apparatus.**—This is attended with the ad-

vantage of indicating all pressures and temperatures, whether above or below the boiling point. His process consists in boiling water in a vessel under a known pressure, and ascertaining the temperature at which it boils. The method depends upon the principle that when the water boils, the steam it produces will have a pressure precisely equal to that to which the water itself is submitted—a principle which is familiar and well established. Thus, for example, the steam produced from water boiled under the ordinary pressure of the atmosphere of 15 lbs. per square inch, has, as is well known, that pressure.

The apparatus consists of a copper boiler *c* (*fig. 51*), closed so as to be steam-tight, filled to about a third of its capacity with water, and placed upon a charcoal furnace. The tubes of four

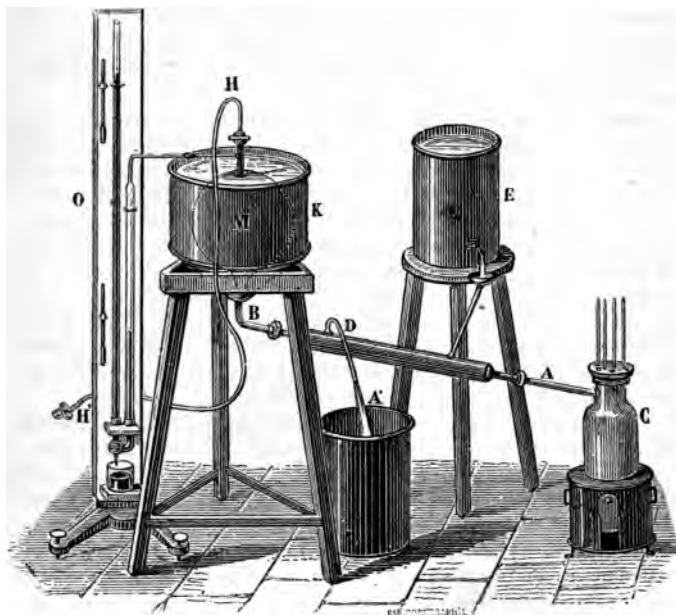


Fig. 51.

thermometers, whose bulbs descend to different depths in it, pass steam-tight through collars in the top. Two of these bulbs are immersed in the upper, and two others in the lower strata of the liquid. The boiler *c* is connected by a tube *A B*, with a large

glass globe *M*, having a capacity of about five gallons, which is filled with air. The tube *AB* is surrounded by a larger tube *V*, which is kept filled with cold water, flowing from a cistern *E*, and discharged into another *A'*. From the upper part of the globe *M*, two tubes proceed, one of which communicates with an air gauge *O*, and the other *H*, is terminated in a connecting piece *H'*, which may be attached at pleasure either to the plate of an air pump, or to that of a condenser, so that the air in *M* can be made to have any degree of pressure, either above or below that of the atmosphere. The globe *M* is immersed in a reservoir of water at the temperature of the surrounding air.

If it be desired to measure the pressure of the vapour of water corresponding to temperatures below the boiling point, the connector *H'* is attached to the plate of an air pump, and the air in *M* is gradually rarefied, so as to assume a series of decreasing pressures below that of the atmosphere. The thermometers in *C* show the temperatures corresponding to these pressures severally, and the gauge *O* shows the corresponding pressures.

If it be desired to ascertain the pressures corresponding to temperatures above the boiling point, the connector *H'* is attached to a condenser or a force pump, by means of which the air in *M* and in the boiler *C* is submitted to a series of increasing pressures above that of the atmosphere. The corresponding temperatures, as before, at which the water boils in *C*, are indicated by the thermometers.

153. Mechanical force developed in evaporation.—When a liquid is converted into vapour, it exerts a certain mechanical force, the amount of which depends on the pressure of the vapour, and the increased volume which the liquid undergoes in evaporation. Thus, if a cubic inch of a liquid swells by evaporation into 2,000 cubic inches of vapour, having a pressure of 10 lbs. per square inch, it is easy to show that a mechanical force is developed in such evaporation which is equivalent to 20,000 lbs. raised through one inch. For, if we imagine a cubic inch of the liquid confined in a tube, the bore of which measures a square inch, it will, when evaporated, fill 2,000 inches of such tube, and, in swelling into that volume, will exert a pressure of 10 lbs., so that it would in fact raise a weight of 10 lbs. through that height. Now, 10 lbs. raised through the height of 2,000 inches, is equivalent to 20,000 lbs. raised through the height of one inch.

Since, however, it is customary to express the mechanical effect by the number of pounds raised through one foot, the

mechanical effect produced in the evaporation of each cubic inch of a liquid will be found by multiplying the number which expresses the volume of vapour produced by the unit of volume of the liquid by the number expressing the pressure of the vapour in pounds per square inch, and dividing the product by 12.

In the following tables the relation between the temperature, pressure, density, volume, and mechanical effect of the vapour of water are given as determined by observation so far as the pressure of twenty-four atmospheres, and by analogy from that to the pressure of fifty atmospheres :—

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TABLE I.

Showing the Pressure, Volume, and Density of the Vapour of Water produced at the Temperatures (in degrees of Fahrenheit's scale) expressed in the first Column, as well as the mechanical Effect developed in the Process of Evaporation.

Temperature Fahr.	Pressure		Volume of Vapour containing Unit of Volume of Water	Density of Vapour in Hundred Millionths of the Density of Water	Mechanical Effect in Lbs. raised 1 Foot	Temperature Fahr.	Pressure		Volume of Vapour containing Unit of Volume of Water	Density of Vapour in Hundred Millionths of the Density of Water	Mechanical Effect in Lbs. raised 1 Foot
	Inches of Mercury	Lbs. per Square Inch					Inches of Mercury	Lbs. per Square Inch			
-4°	0'052	0'0255	650588	154	1383	120°2	3'322	1'63	13154	7602	1785
+5	0'074	0'0363	470898	212	1423	122	3'494	1'71	12546	7970	1791
14	0'104	0'05	342984	292	1451	123°8	3'673	1'80	11971	8354	1796
23	0'144	0'07	251358	398	1480	125°6	3'861	1'89	11424	8753	1802
32	0'199	0'10	182323	540	1483	127°4	4'058	1'99	10901	9174	1807
33°8	0'212	0'10	174495	573	1514	129°2	4'263	2'09	10410	9606	1813
35°6	0'226	0'11	164332	609	1519	131	4'477	2'19	9946	10054	1819
37°4	0'241	0'12	154842	646	1525	132°8	4'700	2'30	9501	10525	1824
39°2	0'257	0'13	145886	686	1531	134°6	4'934	2'42	9082	11011	1830
41	0'274	0'13	137488	727	1536	136°4	5'177	2'54	8680	11523	1836
42°8	0'291	0'14	129587	772	1542	138°2	5'431	2'66	8303	12044	1842
44°6	0'310	0'15	122241	818	1549	140	5'695	2'79	7937	12559	1847
46°4	0'330	0'16	115205	867	1555	141°8	5'973	2'93	7594	13179	1853
48°2	0'351	0'17	108790	919	15-9	143°6	6'258	3'07	7267	13760	1858
50	0'373	0'18	102670	974	1565	145°4	6'558	3'21	6957	14374	1864
51°8	0'397	0'19	99202	1032	1607	147°2	6'869	3'37	6662	15010	1869
53°6	0'422	0'21	91564	1092	1577	149	7'193	3'53	6382	15668	1875
55°4	0'448	0'22	86426	1157	1582	150°8	7'530	3'69	6114	16356	1881
57°2	0'476	0'24	81686	1224	1588	152°6	7'881	3'86	5860	17060	1887
59	0'505	0'25	77008	1299	1590	154°4	8'246	4'04	5619	17797	1893
60°8	0'537	0'27	72913	1372	1598	156°2	8'624	4'23	5386	18566	1898
62°6	0'570	0'28	68923	1451	1604	158	9'019	4'42	5167	19355	1904
64°4	0'604	0'30	65201	1534	1610	159°8	9'427	4'62	4957	20174	1909
66°2	0'641	0'32	61654	1622	1615	161°6	9'852	4'83	4759	21013	1915
68	0'682	0'33	58224	1718	1621	163°4	10'293	5'05	4569	21889	1921
69°8	0'721	0'35	55206	1811	1626	165°2	10'749	5'27	4387	22794	1926
71°6	0'764	0'37	52260	1914	1632	167	11'223	5'50	4204	23789	1928
73°4	0'810	0'40	49487	2021	1638	168°8	11'715	5'74	4048	24702	1937
75°2	0'858	0'42	46877	2133	1644	170°6	12'224	5'99	3891	25699	1943
77	0'909	0'45	44411	2252	1649	172°4	12'752	6'25	3741	26739	1949
78°8	0'963	0'47	42084	2376	1655	174°2	13'298	6'52	3599	27780	1955
80°6	1'019	0'50	39595	2507	1661	176	13'862	6'80	3462	28880	1963
82°4	1'078	0'53	37838	2643	1667	177°8	14'449	7'08	3331	30025	1966
84°2	1'143	0'56	35796	2794	1672	179°6	15'055	7'38	3206	31195	1972
86	1'206	0'59	34041	2938	1678	181°4	15'680	7'69	3087	32329	1977
87°8	1'276	0'63	32291	3097	1684	183°2	16'328	8'00	2973	33537	1983
89°6	1'349	0'66	30650	3263	1689	185	16'996	8'33	2864	34916	1989
91°4	1'425	0'70	29112	3435	1694	186°8	17'688	8'67	2760	36237	1994
93°2	1'506	0'74	27636	3619	1700	188°6	18'401	9'02	2660	37590	2000
95	1'591	0'78	26253	3809	1706	190°4	19'138	9'38	2565	38984	2005
96°8	1'683	0'83	24897	4017	1712	192°2	19'897	9'75	2474	40417	2011
98°6	1'773	0'87	23704	4219	1717	194	20'680	10'14	2387	41891	2017
100°4	1'873	0'92	22513	4442	1722	195°8	21'488	10'53	2304	43405	2023
102°2	1'974	0'97	21429	4666	1728	197°6	22'321	10'94	2224	44956	2028
104	2'087	1'02	20343	4916	1734	199°4	23'179	11'36	2148	46556	2034
105°8	2'196	1'08	19396	5156	1740	201°2	24'062	11'80	2075	48201	2040
107°6	2'315	1'13	18469	5418	1746	203	24'971	12'24	2005	49886	2045
109°4	2'439	1'20	17572	5691	1751	204°8	25'908	12'70	1938	51613	2051
111°2	2'584	1'27	16805	6023	1754	206°6	26'874	13'17	1873	53388	2056
113	2'707	1'33	15938	6274	1762	208°4	27'860	13'66	1812	55191	2062
114°8	2'850	1'40	15185	6585	1768	210°2	28'877	14'16	1751	57055	2066
116°6	3'000	1'47	14472	6910	1774	212	29'921	14'67	1696	58955	2073
118°4	3'158	1'55	13809	7242	1781						

TABLE II.

Showing the Temperature (in degrees of Fahrenheit's scale), Volume, and Density of Vapour of Water, corresponding to Pressures of from 1 to 50 Atmospheres.

From 1 to 24 Atmospheres obtained by Observation.

„ 24 to 50 „ „ „ „ „ Analogy.

Pressure, Atmospheres	Temperature, Fahrenheit	Volume of Vapour produced by Unit of Volume of Water	Density of Vapour (Density of Water=1)	Pressure, Atmospheres	Temperature, Fahrenheit	Volume of Vapour produced by Unit of Volume of Water	Density of Vapour (Density of Water=1)
1	212	1696	0'0005895	13	380'66	163'74	6107
1½	233'96	1167'8	8563	14	386'96	153'10	6527
2	250'52	897'09	0'0011147	15	392'90	144'00	6944
2½	263'84	731'39	13673	16	398'48	135'90	7359
3	275'18	619'19	16150	17	403'88	128'71	7769
3½	285'08	537'96	18589	18	408'92	122'28	8178
4	293'72	476'26	20997	19	413'78	116'51	8583
4½	300'38	427'18	23410	20	418'46	111'28	8986
5	307'58	388'16	25763	21	422'96	106'53	9387
5½	314'24	355'99	28091	22	427'28	102'19	9785
6	320'36	328'93	30402	23	431'42	98'21	0'010182
6½	326'30	305'98	32683	24	435'56	94'56	10575
7	331'70	286'12	34911	25	439'34	91'17	10968
7½	336'92	268'82	37217	30	457'16	77'50	12903
8	341'78	253'59	39434	35	472'64	68'20	14663
9	350'78	227'98	43865	40	486'50	60'08	16644
10	358'88	207'36	48226	45	499'10	54'06	18497
11	366'80	190'27	52557	50	510'62	49'31	20306
12	374'00	175'96	56834				

154. **Regnault's Tables for Steam and other Vapours.**—

On account of their importance we give in this article Regnault's results of his experiments on the maximum pressure of steam and other vapours. The temperature is in these tables expressed in degrees of the Centigrade Scale, while the pressure is given in millimetres. Thus, for example, at the temperature of -32°C ., the pressure of saturated steam on the unit surface is equal to the weight of a column of mercury, having the unit surface for its base, and being 0'320 millimetres long; at the temperature of 100°C . the pressure of saturated steam balances a volume 760 millimetres long, and so on.

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TABLE I.

Maximum Tension of Water-vapour between -32° and $+230^{\circ}$.

Tempe- rature	Pressure	Tempe- rature	Pressure	Tempe- rature	Pressure	Tempe- rature	Pressure
	Millimetres		Millimetres		Millimetres		Millimetres
-32	0.320	-31	0.352	-30	0.386	-29	0.424
-28	0.464	27	0.508	26	0.555	25	0.605
24	0.660	23	0.719	22	0.783	21	0.853
20	0.927	19	1.008	18	1.095	17	1.189
16	1.290	15	1.400	14	1.518	13	1.646
12	1.783	11	1.933	10	2.093	9	2.267
8	2.455	7	2.658	6	2.876	5	3.113
4	3.368	3	3.644	2	3.941	1	4.263
+ 0	4.600	+ 1	4.940	+ 2	5.302	+ 3	5.687
4	6.097	5	6.534	6	6.998	7	7.492
8	8.017	9	8.574	10	9.165	11	9.792
12	10.457	13	11.162	14	11.908	15	12.699
16	13.536	17	14.421	18	15.357	19	16.346
20	17.391	21	18.495	22	19.659	23	20.888
24	22.184	25	23.550	26	24.988	27	25.505
28	28.101	29	29.782	30	31.548	31	33.406
32	35.359	33	37.411	34	39.565	35	41.827
36	44.201	37	46.691	38	49.302	39	52.039
40	54.906	41	57.910	42	61.055	43	64.346
44	67.790	45	71.391	46	75.158	47	79.093
48	83.204	49	87.499	50	91.982	51	96.661
52	101.543	53	106.636	54	111.945	55	117.478
56	123.244	57	129.251	58	135.505	59	142.015
60	148.791	61	155.839	62	163.170	63	170.791
64	178.714	65	186.945	66	195.496	67	204.376
68	213.596	69	223.165	70	233.093	71	243.393
72	254.073	73	265.147	74	276.624	75	288.517
76	300.838	77	313.600	78	326.811	79	340.488
80	354.643	81	369.287	82	384.435	83	400.101
84	416.298	85	433.041	86	450.344	87	468.221
88	486.687	89	505.759	90	525.450	91	545.778
92	566.757	93	588.406	94	610.740	95	633.778
96	657.535	97	682.029	98	707.280	99	733.305
100	760.000	101	787.590	102	816.010	103	845.280
104	875.410	105	906.410	106	938.310	107	971.140
108	1004.91	109	1039.65	110	1075.37	111	1112.09
112	1149.83	113	1188.61	114	1228.47	115	1269.41
116	1311.47	117	1354.66	118	1399.02	119	1444.55
120	1491.28	121	1539.25	122	1588.47	123	1638.96

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TABLE I (continued).

Tempe- rature	Pressure	Tempe- rature	Pressure	Tempe- rature	Pressure	Tempe- rature	Pressure
°	Millimetres	°	Millimetres	°	Millimetres	°	Millimetres
124	1690·76	125	1743·88	126	1798·35	127	1854·20
128	1911·47	129	1970·15	130	2030·28	131	2091·94
132	2155·03	133	2219·69	134	2285·92	135	2353·73
136	2423·16	137	2494·23	138	2567·00	139	2641·44
140	2717·63	141	2795·57	142	2875·30	143	2956·86
144	3040·26	145	3125·55	146	3212·74	147	3301·87
148	3392·98	149	3486·09	150	3581·23	151	3678·43
152	3777·74	153	3879·18	154	3982·77	155	4088·56
156	4196·59	157	4306·88	158	4419·45	159	4534·36
160	4651·62	161	4771·28	162	4893·36	163	5017·91
164	5144·97	165	5274·54	166	5406·69	167	5541·43
168	5678·82	169	5818·90	170	5961·66	171	6107·19
172	6255·48	173	6406·60	174	6560·55	175	6717·43
176	6877·22	177	7039·97	178	7205·72	179	7374·52
180	7546·39	181	7721·37	182	7899·52	183	8080·84
184	8265·40	185	8453·23	186	8644·35	187	8838·82
188	9036·68	189	9237·95	190	9442·70	191	9650·93
192	9862·71	193	10078·04	194	10297·01	195	10519·63
196	10745·95	197	10975·00	198	11209·82	199	11447·46
200	11688·96	201	11934·37	202	12183·69	203	12437·00
204	12694·30	205	12955·66	206	13221·12	207	13490·75
208	13764·53	209	14042·52	210	14324·80	211	14611·32
212	14902·22	213	15197·48	214	15497·17	215	15801·33
216	16109·94	217	16423·15	218	16740·90	219	17063·29
220	17390·36	221	17722·13	222	18058·64	223	18399·94
224	18746·07	225	19097·04	226	19452·92	227	19813·76
228	20179·61	229	20550·48	230	20926·40		

TABLE II.

Tension of Vapours in Millimetres.

Tempe- rature	Ether	Alcohol	Chloro- form	Tetra- chloride of Carbon	Sulphide of Carbon	Benzene	Turpen- tine
° C.							
- 20	68·90	3·34	—	9·80	47·30	5·79	—
10	114·72	6·47	—	18·47	79·44	12·92	—
0	184·39	12·70	—	23·95	127·91	25·31	2·07
+ 10	286·83	24·23	—	55·97	198·46	45·25	2·94

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TABLE II (continued).

Temperature	Ether	Alcohol	Chloroform	Tetra-chloride of Carbon	Sulphide of Carbon	Benzene	Turpentine
20	432°78	44°46	160°47	90°99	298°03	75°65	4°45
30	634°80	78°52	247°51	142°27	434°62	120°24	6°87
40	907°04	133°69	369°26	214°81	617°53	183°62	10°80
50	1264°83	219°90	535°05	314°38	857°07	271°37	16°98
60	1725°01	350°21	755°44	447°43	1164°51	390°10	26°46
70	2304°90	541°15	1042°11	621°15	1552°09	547°42	40°64
80	3022°79	812°91	1407°64	843°29	2032°53	751°86	61°30
90	3898°26	1189°30	1865°22	1122°26	2619°08	1012°75	90°61
100	4953°30	1697°55	2428°54	1467°09	3325°15	1340°05	131°11
110	6214°63	2367°64	3110°99	1887°44	4164°06	1744°12	185°62
120	7719°20	3231°73	3925°74	2393°67	5184°79	2235°44	257°21
130	—	4323°00	4885°10	2996°88	6291°60	2824°35	348°98
140	—	5674°59	6000°16	3709°04	7603°96	3520°73	464°02
150	—	7318°40	7280°62	4543°13	9095°94	4333°71	605°20
160	—	—	8734°20	5513°14	—	5271°43	775°09
170	—	—	—	6634°37	—	6340°72	975°42
180	—	—	—	7923°55	—	—	1207°92
190	—	—	—	9399°02	—	—	1473°24
200	—	—	—	—	—	—	1771°47

TABLE III.

Tension of Vapours of Liquefied Gases, and of Mercury.

Liquefied Gases				Mercury			
Temperature	Sulphurous Anhydride	Ammonia	Sulphydic Acid	Temp.	Tension in millimetres	Temp.	Tension in millimetres
° C	Millimetres	Millimetres	Millimetres	° C		° C	
-78°2	—	240°0	441°4	0	0°0200	120	1°534
40	—	528°6	—	10	0°0268	150	4°266
30	287°5	876°6	2808°6	20	0°0372	180	11°00
20	479°5	1397°7	4273°0	30	0°0530	200	19°90
10	762°5	2149°5	5945°0	40	0°0767	250	75°75
0	1165°1	3162°9	7709°3	50	0°1120	300	242°1
+ 10	1719°5	4612°2	10896°3	60	0°1643	350	663°2
20	2462°0	6467°0	14151°5	70	0°2410	400	1587°9
30	3431°8	8832°2	18035°3	80	0°3528	450	3384°3
40	4670°2	11776°4	22582°5	90	0°5142	500	6520°2
50	6220°0	—	27814°8	100	0°7455	520	8264°9

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The following table, by Messrs. *Fairbairn* and *Tate*, may be considered as a continuation of Table I., art. 153. It gives for a portion of that table more recent results, and extends these beyond the ordinary pressure of the atmosphere. Its object is to state the temperatures at which water is completely converted into saturated steam under various pressures, together with the volume of steam formed under these circumstances compared with that of the water from which it is produced.

Pressure, Temperature, and Volume of Saturated Steam.

Pressure		Temperature		Volume
Engl. Inches	Millimetres	Fahrenheit	Centigrade	
5'35	135'9	136'77	58'20	8275'3
8'62	219'9	155'33	68'51	5333'5
9'45	240'0	159'36	70'76	4920'2
12'47	316'7	170'92	77'18	3722'6
12'61	320'2	171'48	77'49	3715'1
13'62	345'9	174'92	79'40	3438'1
16'01	406'6	182'30	83'49	3051'0
18'36	466'3	188'30	86'83	2623'4
22'88	581'2	198'78	92'66	2149'5
53'61	1361'7	242'90	117'16	943'1
55'52	1410'1	244'82	118'23	908'0
55'89	1419'6	245'22	118'45	892'5
66'84	1697'7	255'50	124'16	759'4
76'20	1935'4	263'14	128'41	649'2
81'53	2070'8	267'21	130'67	635'3
84'20	2138'9	269'20	131'77	605'7
90'08	2287'9	273'30	134'05	584'4
92'23	2342'6	274'76	134'86	573'2
99'60	2529'8	279'42	137'45	515'0
104'54	2655'2	282'58	139'21	497'2
112'78	2864'6	287'25	141'80	458'3
114'25	2901'9	288'25	142'36	449'6
122'25	3105'1	292'53	144'74	433'1

155. Specific gravities of vapours.—These, like those of gases, are usually referred to air as a standard, the air being supposed to have the standard temperature of 0°, the barometer standing at 30 inches. The density of vapours, however, is a

term frequently used to express the ratio of a given volume of the vapour to an equal volume of air, having the same temperature and pressure.

It has been ascertained experimentally that in the case of steam, at all temperatures above 20° this ratio is invariable, the steam being supposed to be saturated.

156. **Gay-Lussac's apparatus.**—The apparatus by which the density of vapour, in this sense of the term, was ascertained

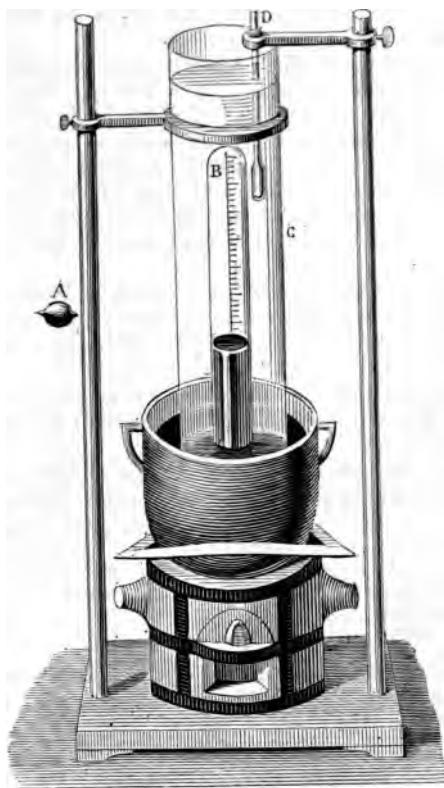


Fig. 52.

by Gay-Lussac, is represented in *fig. 52*. A graduated glass tube *B* of large diameter is filled with mercury, and, being in-

verted in the usual manner, is plunged in a cistern of mercury. The mercury will be sustained in the tube *B* by the atmospheric pressure. A small and thin bulb of glass *A* is filled through an opening in a small tube projecting from it, with the liquid whose vapour is to be examined, and hermetically sealed. This ball is let into the mouth of the tube *B*, and being lighter than mercury it ascends to the top through the mercury. The tube *B* is then surrounded by a glass cylinder *C*, open at both ends, the lower end being immersed in the mercury; this cylinder is then filled with water or oil to a level above the top of the tube *B*, and a thermometer *D* is immersed in it.

The furnace upon which the cistern is placed being then lighted, the mercury in the tube *B* is heated. The bulb *A* will soon burst by reason of the expansion of the liquid it contains, and the liquid once liberated will begin to produce vapour, the pressure of which will cause the mercury in the tube *B* to descend. The thermometer *D* will then indicate the temperature of the vapour in *B*, and the difference between the height of the mercury in *B* and that of the barometer will indicate its pressure.

The weight of the vapour being known by knowing that of the liquid which was contained in the bulb *A*, its density, at each temperature which it attains, can be determined and can be compared with that of air at the same temperature.

It was found that the ratio of these densities is constant for the vapour of most liquids at all temperatures which are above their boiling points.

The following are those ratios for the undermentioned vapours, the density of air being denoted by the number 10000 :—

Air	10000	Vapour of essence of tur-	
Vapour of water . . .	6325	pentine . . .	50130
" alcohol . . .	16138	" mercury . . .	6976
" sulphuric ether .	25860	" ioline . . .	8716
" sulphide of			
carbon . . .	26447		

A most valuable modification of Gay-Lussac's method has lately been devised by Professor Hofmann, who employs a graduated glass tube closed at one end, about 1000 millimetres in length, and 15—20 millimetres in width, which is filled with mercury, and the open end inserted in a vessel containing mercury. It is surrounded by a cylindrical glass jacket, through which, according to the temperature at which the determination is to be made, a current of the vapour of boiling alcohol, water, aniline, or some other substance of constant

boiling point, is urged, whereby the substance previously introduced into the tube in a minute stoppered glass bottle is converted into vapour. The volume which the vapour occupies, the temperature to which it is heated, the height of the mercury column in the tube, and the atmospheric pressure are noted; the weight of a quantity of air, which at the same temperature and under the same pressure would occupy the same volume as the vapour of the amount of substance taken is then calculated, and by dividing this weight of air into the weight of substance taken, the vapour density of the substance in question, as compared with the air, is ascertained.

The boiling points of all substances, as has been shown previously, are considerably lowered by a reduction of pressure, and moreover, the tendency to decompose which many substances exhibit at temperatures close to their boiling points under ordinary pressures, is obviously greatly lessened by diminishing the pressure. Now, it is evident that when a tube like that above described is inverted there will be a considerable empty space at the top of the mercury; into this the substance volatilises, and is converted into vapour under reduced pressure, and therefore at a temperature much lower than its boiling point under ordinary conditions. For example, the vapour density of aniline, which boils at 182° under a pressure of 760 millimetres of mercury, may be in this way determined by heating the tube by the vapour of boiling water (100°); hence the great value of this modification, and its superiority over Gay-Lussac's original method.

157. Dumas' Method.—By the method of Gay-Lussac the volume which a given weight of the substance occupies in the gaseous state is ascertained. Dumas has designed a method by which we determine the weight of a given volume of the gas as vapour. The method may best be explained by an example. Suppose, then, that we wish to obtain the specific gravity of alcohol vapour. We take a light glass globe having a capacity of from 400 to 500 cubic centimetres, and draw the neck out in the flame of a lamp, so as to leave only a fine opening. The first step is now to ascertain the weight of the glass globe when completely exhausted of air. As this cannot readily be done directly, we weigh the globe full of air, and then subtract the weight of the air, ascertained by calculation from the capacity of the globe and from the temperature and pressure of the air. One cubic centimetre of dry air at 0° and a barometric pressure of 760 millimetres weighs 0.001292 grammes; it follows from the principles previously explained in connection with the rate

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of expansion of gases, and from Mariotte's law, that the weight of one cubic centimetre of dry air at an atmospheric pressure of H millimetres and at temperature t degrees will weigh—

$$0.001293 \times \frac{1}{1 + 0.003665t} \times \frac{H}{760}$$

grammes, and this multiplied by the capacity of the globe in cubic centimetres, which we may call V , will give us the required weight of the air in the globe. Call this weight w , and the weight of the globe and air W , then $W - w$ is the weight of the globe exhausted of air.

The second step is to ascertain the weight of the globe filled with alcohol vapour at a known temperature and under a known pressure. For this purpose we introduce into the globe a few grammes of pure alcohol, mount the globe upon a suitable support, and sink it beneath some oil contained in an iron vessel. After reversing it in this position, we slowly raise the temperature of the oil to between 300° or 400° , which we observe by means of a thermometer. The alcohol is converted into vapour and drives out the air with which the excess of vapour escapes at the fine opening. When the bath has acquired the requisite temperature we close the fine opening by suddenly melting the end of the tube with a mouth blowpipe, and as nearly as possible at the same moment observe the temperature of the bath and the height of the barometer. We have now the globe filled with alcohol vapour at a known temperature and under a known pressure. Since it is hermetically sealed, its weight cannot change, and we can therefore allow it to cool, clean it, and weigh it at our leisure. This will give us the weight of the globe filled with alcohol vapour at a known temperature, t' , and under a known pressure, H' . Call this weight W' . The weight of the vapour is $W' - (W - w)$. The third step is to ascertain the weight of the same volume of air at the same temperature and under the same pressure. This can easily be found, from the principles already explained, by calculation. The last step is to find the capacity of the globe, which, although we have supposed it known (V), is not actually ascertained experimentally until the end of the process. For this purpose we break off the tip of the tube under mercury, which, if the experiment has been carefully conducted, rushes in and fills the globe completely. We then empty this mercury into a carefully graduated glass cylinder and read off the volume. We find then the specific gravity by dividing the weight of the vapour by the weight of the air. The formulæ for the calculations are these—

$$\begin{aligned}
 &\text{Weight of the globe and air.} \dots\dots\dots W \\
 &\text{,, ,, ,, air} = w = 0\cdot001292 \times V \times \frac{1}{1 + 0\cdot00366t} \times \frac{H}{760} \\
 &\text{,, ,, ,, globe exhausted of air} \dots\dots\dots W - w \\
 &\text{,, ,, ,, ,, filled with vapour at the temperature } t' \\
 &\quad \text{and under a pressure } H' \dots\dots\dots W' \\
 &\text{,, ,, ,, vapour} \dots\dots\dots W' - W + w \\
 &\text{,, ,, ,, air at } t' \text{ and under a pressure } H' = \\
 &\quad 0\cdot001292 V (1 + 0\cdot00003t') \times \frac{1}{1 + 0\cdot00366t'} \times \frac{H'}{760} \\
 &\text{Specific gravity} = \frac{W' - W + w}{0\cdot001292 V (1 + 0\cdot00003t') \times \frac{1}{1 + 0\cdot00366t'} \times \frac{H'}{760}}
 \end{aligned}$$

158. **Mixture of gases and vapours.**—When a gas and vapour which exert no mutual chemical action are inclosed in the same space, they will exercise separately on the confining surfaces precisely the same pressures which each would produce if it occupied the same space in the absence of the other, and consequently, the total pressure which their mixture will produce will be equal to the sum of the pressures which they would produce separately.

The apparatus by which Gay-Lussac established experimentally this important law is shown in *fig. 53*, and consists of a glass tube B, of large bore, having iron caps furnished with stop-cocks, *a*, *d*, cemented on to the top and bottom. It communicates by a horizontal branch, having a stop-cock *c*, with another vertical tube A, of much smaller bore and greater height. A graduated scale is placed between these tubes so as to indicate the height of the column in each of them.

The stop-cock *d* being closed and *a* and *c* opened, let mercury be poured into the tube B until it rises to the level of the stop-cock *a*. Since there is free communication between the two tubes, the mercury will rise to the same height in the lesser tube A. *c* is a funnel, having a stop-cock *b*, which can be screwed upon the tube proceeding from the stop-cock *a*. The stop-cock *b* is constructed in a peculiar manner. Instead of being pierced as usual by a hole passing quite through it, the hole passes only half through it, so that in no position can it open a free communication between the funnel *c* and the tube B.

A bulb F is provided, furnished with a stop-cock *f*, in which dry air or gas can be condensed, and which also can be screwed upon the neck of the stop-cock *a*.

Now, let us suppose dry air or gas to be condensed in the bulb F, the stop-cock *f* being closed. Let the funnel *c* be un-

screwed from the neck of the stop-cock *a*, the mercury being still at the level of the stop-cock *a* in both tubes. Let the bulb *r* be now screwed on, and let the stop-cock *f* be opened. The column of mercury in *B* is now subject to the pressure of the

condensed air or gas in the bulb, while the column in the tube *A* is subject to the lesser pressure of the atmosphere; it follows that the column of mercury in the tube *B* will descend, and the column in *A* will rise, until the difference of their heights represents the excess of the pressure of the gas above the mercury in *B* over that of the atmosphere. Let the cock *a* be now closed, and let the cock *d* be opened, so that a portion of the mercury in the tubes shall fall into the cistern *H*. The space occupied by the air or gas in the tube *B* being thus gradually enlarged, the pressure of the gas will be proportionally diminished, and will at length be reduced to that of the atmosphere. The moment when this takes place will be known by observing when the column of mercury in the tube *A* falls to the exact level of the column in the tube *B*. When this takes place let the cock *d* be closed; we shall then have a portion of dry air or gas above the mercury in the tube *B*, having a pres-

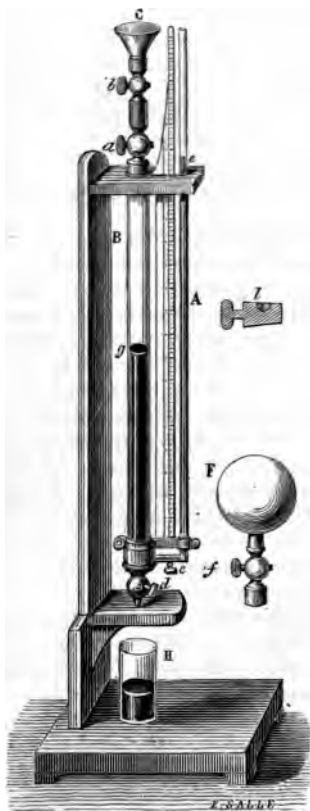


Fig. 53.

sure exactly equal to that of the atmosphere.

The bulb *r* being removed from the neck of the stop-cock *a*, let the funnel *c* be screwed on in its place, and let a portion of the liquid whose vapour is under observation be poured into the funnel. If the stop-cock *b* be turned with its cavity upwards,

the cavity will be filled with the liquid, and if the stop-cock *b* be then turned half round, the stop-cock *a* being previously opened, the drop of liquid in the cavity will fall into the tube *B*, where it will float upon the mercury; and by repeating this process, as many drops as may be desired can be thus let in.

When a portion of the liquid has thus been let in upon the mercury and is enclosed by shutting the stop-cock *a*, a part of it will evaporate, and the vapour will be mixed with the air in the tube *B*; and at the same time the column of mercury in the tube *A*, which was at the level of the mercury in *B*, will rise above it, and will continue to rise until the space in the tube *B* has been saturated with vapour.

Now, if the difference between the heights of the columns in the two tubes be observed, it will be found to be exactly equal to the height of a column which would balance the pressure of the vapour of the liquid, saturating the space in the tube *B*, if no air or gas were present there.

It follows, therefore, from this, that the pressure of the air or gas with which the vapour is mixed does not in any respect change or modify the effect produced by the pressure of the vapour.

This experiment may be varied by varying the temperature to which the tube *B* is exposed. It will be found in all cases that the difference between the columns of mercury in the two tubes represents exactly the pressure of the vapour, which would saturate the space in the tube *B*, at the temperature to which it is exposed.

159. Liquids having different temperatures communicating in closed vessels.—If a closed vessel in which a liquid is raised to an elevated temperature, communicate with another vessel which is maintained at a lower temperature, the vapour evolved by the liquid at the higher temperature, will nevertheless have the pressure corresponding to the lower temperature. This is easily ascertained experimentally, by applying any pressure gauge to the vessel in which the liquid is maintained at the higher temperature. The fact is easily explained by the partial condensation which the vapour constantly suffers in the colder vessel.

160. Spheroidal state of liquids.—If a small drop of water, or certain other liquids, be let fall from a funnel, terminating in a small and fine tube, upon a surface of metal rendered red hot, the following remarkable phenomena will be manifested :—

1°. The liquid will not wet the surface, but will appear to

avoid touching it, and will assume a globular form like that which water assumes when it is diffused upon a greasy surface, or like globules of mercury upon glass.

2°. Instead of entering into violent ebullition, as might be expected, the temperature of the liquid will be very little affected, and the drop of liquid will either remain at rest or be affected with gyratory motion.

3°. When the surface on which it rests is cooled down to a temperature which varies with each liquid, and is more elevated the higher the boiling point of the liquid, the latter will begin to diffuse itself on the surface, ebullition will begin, and the liquid will be suddenly scattered with violence in all directions. For water, the dish must have at least a temperature of 200° ; for alcohol, 134° ; and for ether, 61° .

These experiments, usually named *Leidenfrost's* after their discoverer, can be most conveniently made with a shallow capsule of metal shaped like a watch glass, which may be rendered white hot by a powerful lamp. The liquid may be let fall upon it in small drops by a finely pointed pipette or funnel.

161. **Boutigny's experiments.**—M. Boutigny, who has made numerous experiments on these phenomena, appears to have demonstrated that in such cases the globule of liquid is not in contact with the incandescent metal, but, on the contrary, is separated from it by a space of sensible magnitude. He affirms that, directing his eye between the globule and the red-hot surface, he has seen distinctly in the intervening space objects on the other side of the globule. This phenomenon has not yet been clearly and satisfactorily explained; but it is generally supposed that around the globule an atmosphere of vapour is formed, which has sufficient elasticity to prevent the contact of the globule with the metal. The liquid composing the drop, being thus prevented from contact with the metal, receives no heat from it, except that which comes by radiation; and being more or less diathermanous, the chief part of this passes through it without affecting its temperature. Indeed, as long as the liquid in the hot capsule remains in the spheroidal state, its temperature is always below its boiling point. Boutigny found, by means of a very delicate thermometer, that the temperature of water in the spheroidal state was 95° , that of alcohol 75° , of ether 34° , and of liquid sulphurous acid -11° . It appears, however, that the temperature of the disengaged vapour is as high as that of the vessel itself.

Among the experiments of M. Boutigny is one which is so striking in its result as to merit a special notice. A capsule of platinum being rendered white-hot, a small quantity of anhy-

drous sulphurous acid in the liquid state is poured upon it. The boiling point of this liquid being so low as -10° , its temperature in the liquid state is usually much lower; and as it continues in the liquid state upon the white-hot metal, the two bodies are thus exhibited nearly in contact, one having the temperature of 400° or 450° , and the other below -10° . A few drops of water are then let fall upon the liquid acid, and, notwithstanding their proximity to the white-hot metal, they are instantly congealed.

To the same class of phenomena belongs an effect with which everyone who has frequented forges or ironworks is familiar. If a bar of iron or steel, rendered white hot, be plunged suddenly in water it will continue for some moments without perceptibly affecting or being affected by the water; it will retain its incandescence, and will produce neither hissing nor effervescence. It is only when its temperature has been lowered that these effects will be manifested.

162. Vapour separated from a liquid obeys the laws of expansion by heat like any gaseous body.—In the tables, on pages 165, 167, etc., the vapour is considered as being in the state of the greatest density which is compatible with its temperature. But it must be remembered that vapour separated from the liquid may, by receiving heat from any external source, be raised like so much air, or other gaseous fluid, to any temperature whatever, and that the elevation of its temperature under such circumstances is attended with the same effects as in the case of atmospheric air. If it be so confined as to be incapable of expansion, its pressure will be augmented a $\frac{1}{273}$ rd part for each degree of the centigrade scale through which its temperature rises; and if it be capable of expanding under an uniform pressure, then its volume will be augmented in the same ratio.

163. Properties of superheated vapour.—Vapour which receives a supply of heat after it has been separated from the liquid, and which has therefore been denominated *superheated vapour*, has some important properties which distinguish it from the vapour which proceeds directly from the liquid.

The vapour which proceeds directly from a liquid by the process of evaporation, contains no more heat than is essential to its maintenance in the vaporous form. If it lose any portion of this heat, a part of it will become liquid; and the more it loses, the more will return to the liquid state, until, being deprived of all the heat which it had received in the process of evaporation, the whole of the vapour will become liquid.

But, in the case of superheated vapour, the effects are different. Such vapour may lose a part of its heat, and still continue to be vapour. In fact, no part of it can be reduced to the liquid state until it lose all the heat which had been imparted to it after evaporation.

164. **Effects of mere compression.**—It is sometimes affirmed that vapour may, by mere mechanical compression, be reduced to the liquid state. This requires some explanation; without it, it is true neither in relation to vapour raised directly from liquids, nor super-heated vapour.

If vapour raised directly from a liquid at any proposed pressure, be, after separation from the liquid, either compressed into a diminished volume, or allowed to expand into an increased volume, its temperature will be raised in the one case and lowered in the other; and, at the same time, its pressure will be augmented by the diminution and diminished by the augmentation of volume. It will be found, however, that the temperature, pressure, and volume will in every case be exactly those which the vapour would have had if it had been directly raised from the liquid at that temperature and pressure.

Thus, the vapour raised from water at the temperature of 68° F. has a volume 58,224 times greater than the water that produced it (see Table I. p. 165). Now let this vapour, being separated from the water, be compressed until it be reduced to a volume which is only 1,696 times that of the water which produced it, then its temperature will rise to 212° , exactly that which it would have had if it had been directly raised from the water under the increased pressure to which it has been subjected.

In the same manner, whatever other pressure the vapour may be submitted to, it will still, after compression, continue to be vapour, and will be identical in temperature and volume with the vapour which would be raised from the same liquid directly if evaporated under the increased pressure.

Although mere compression cannot reduce any part of a volume of vapour to the liquid state, it will facilitate such a change by raising the temperature of the vapour without augmenting the quantity of heat it contains, and thereby rendering it possible to abstract heat from it. Thus, for example, if a volume of vapour at the temperature of 0° be given, it may be difficult to convert any portion of it into a liquid, because heat cannot be easily abstracted from that which has already a temperature so low. But if this vapour, by compression, and without receiving any accession of heat, be raised to the temperature

of 100° , it can easily be deprived of a part of its heat by placing it in contact with any conducting body at a lower temperature; and the moment it loses any part of its heat, however small, a portion of it will be reduced to the liquid state.

165. Permanent gases are superheated vapours.—It may be considered as certain that all that class of bodies which are denominated permanent gases are the superheated vapours of substances which, under other thermal conditions, would be found in the liquid or solid state. It is easy to conceive a thermal condition of the globe which would render it impossible that water should exist save in the state of vapour. This would be the case, for example, if the temperature of the atmosphere were 100° with its present pressure. A lower temperature, with the same pressure, would convert alcohol and ether into permanent gases.

166. Processes by which gases have been liquefied and solidified.—The numerous experiments by which many of the gases hitherto regarded as permanent have been condensed and reduced to the liquid, and, in some cases, to the solid state, have further confirmed the inferences based on the preceding physical principles. The principle on which these experiments have in general been founded is, that if, by any means, the heat which a superheated vapour has received after having assumed the form of vapour can be taken from it, the condensation of a part of it must necessarily attend any further loss of heat, since, by what has been explained, it will be apparent that no heat will remain in it except what is essential to its maintenance in the vaporous state.

The gas which it is desired to condense is first submitted to severe compression, by which its temperature is raised either by diminishing its specific heat or by rendering sensible the heat that was previously latent in it. The compressed gas is at the same time surrounded by some medium which is at a very low temperature; so, that, as fast as heat is developed by compression, it is absorbed by the surrounding medium.

When, by such means, all the heat by which the gas has been surcharged has been abstracted, and when no heat remains save what is essential to the maintenance of the elastic state, the gas is in a thermal condition analogous to that of vapour which has been directly raised by heat from a liquid, and which has not received any further supply of heat from any other source. It follows, therefore, that any further abstraction of heat must cause the condensation of a corresponding portion of the gas.

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167. **Gases which have been liquefied.**—The following are some of the gases which, being kept at the constant temperature of 0° by depriving them of heat as fast as their temperature was raised by compression, have been reduced to the liquid state. The pressures necessary to accomplish this are here indicated :—

Name of Gases condensed	Pressure under which Condensation took place
	Atmospheres
Sulphurous acid	1·5
Cyanogen gas	2·3
Hydriodic acid	4·0
Ammoniacal gas	4·4
Hydrochloric acid	8·0
Nitrous Oxide	37·0
Carbonic acid	39·0

If these substances be regarded as liquids, the above pressures would be those under which they would vaporise at 0° . If they be regarded as vapours, they are the pressures under which they would be condensed at 0° .

M. Pouillet succeeded in condensing some of these gases at the following higher temperatures and greater pressures :—

Gas	Temperature Fahrenheit	Pressure Atmospheres
Sulphurous acid	46·4	2·5
Ammoniacal gas	50	5
Nitrous Oxide	51·8	43
Carbonic acid	50	45

Hydrochloric acid has been liquefied under a pressure of 40 atmospheres, at the temperature of 9° .

168. **Experiments of M. Pouillet.**—The apparatus used in these experiments consisted of two glass tubes A B (*fig. 54*) of small and perfectly uniform calibre, each 80 inches long. Their lower ends were inserted in a block of cast iron, D, communicating by a horizontal tube C, with a massive cast-iron reservoir C, the lower part of which is filled with mercury, and the upper part with oil. A solid plunger *d* passes through an oil-tight collar and stuffing-box *e*, and is urged by a screw *E*, turned by a powerful handle *F*. When the screw is turned, so as to cause

the plunger *d* to descend into the reservoir, the oil which it displaces forces an equal volume of mercury from the reservoir into the tubes *A*, *B*.

The diameters of the tubes *A*, *B*, were about the 10th of an inch. The gases operated upon, being previously obtained perfectly dry and pure, are introduced into the tubes at the top; and when filled with them, the tops are closed by the blow-pipe.

By this apparatus M. Pouillet was able to obtain a compressing force of the prodigious intensity of 100 atmospheres, which is equivalent to a pressure of 1500 lbs. per square inch.

The liquids produced by the compression of carbonic acid and the nitrous oxide, were perfectly limpid and colourless. That produced by ammoniacal gas had a yellowish green colour.

169. **Carbonic acid.**—Of all the gases which have been liquefied, that which presents circumstances of the greatest interest is carbonic acid. We shall, therefore, here briefly describe this gas, and show the process by which it has been reduced, not merely to the liquid, but even to the solid state.

Carbonic acid is a colourless æriform fluid, nearly without odour, and having a slightly acid flavour. Bulk for bulk, it is heavier than air in the proportion of nearly 3 to 2; and this relative weight is such, that if the surrounding air be not agitated, the gas may be poured from one vessel, *A*, *fig. 55*, to another vessel, *B*, as a liquid would be.

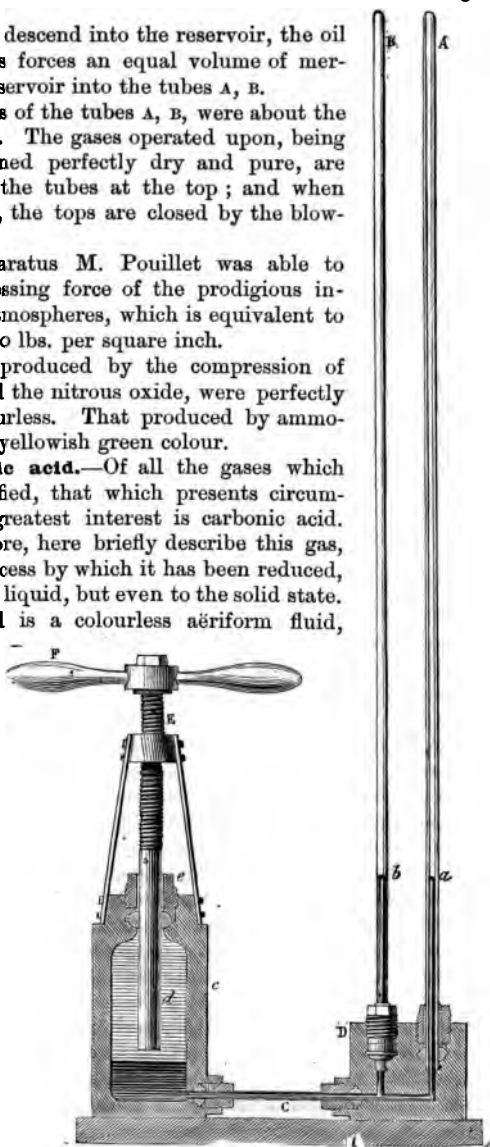


Fig. 54.

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There are various methods of producing this gas, one of which consists in putting pieces of marble in a flask, *A*, *fig. 56*. The flask is then nearly half filled with water; a glass tube terminating with a funnel above, passes, air-tight, through its neck, *b*, the lower end descending below the level of the water. Another glass tube twice bent as shown in the figure is inserted, air-tight, in a second neck, *a*, the other end of which dips down below the surface of the water in an adjacent vessel, in which a flask, previously filled with water, is inverted, the end

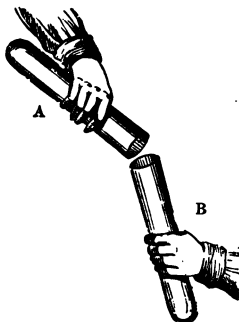


Fig. 55.

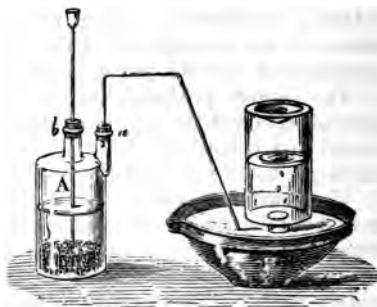


Fig. 56.

of the tube, turned upwards, entering the mouth of this flask. At the commencement of the process, the atmospheric pressure acting on the surface of the water in the vessel, prevents the water from falling out of the flask, and keeps it filled.

A small quantity of hydrochloric acid is now poured into the vessel *A* through the tube which passes through the neck *b*; this, mixing immediately with the water, forms a solution which produces a strong chemical action on the marble. Marble being a substance whose constituents are carbonic acid and lime, and the hydrochloric acid having a much stronger chemical attraction than the carbonic acid has for the lime, tears the latter from it, liberating the carbonic acid, which rises in the gaseous state to the upper part of the flask, *A*, passes through the neck *a*, then through the bent tube, and, rising in bubbles through the water in the inverted flask, collects in the upper part of it, pressing the water downwards, as shown in the figure.

This gas is so soluble in water, that it mixes intimately with it, so that under the ordinary pressure and temperature of the atmosphere, water in contact with carbonic acid will absorb its

own bulk of that gas ; but what is more remarkable, it will still absorb its own bulk to whatever extent the density of the gas may be increased. Thus, if a gallon of water be in contact with carbonic acid, under the atmospheric pressure, it will absorb a gallon of that gas. If the pressure be two atmospheres, it will still absorb a gallon, but that gallon will contain twice as much carbonic acid as the former, in consequence of the double compressing force. In the same manner, if it be subject to the pressure of three atmospheres, it will absorb three times the quantity of the gas, and so on.

If water which has thus absorbed a large quantity of carbonic acid, in consequence of the pressure exerted upon it, be suddenly relieved from that pressure, the gas previously absorbed will immediately escape, rising from every part of the water in small bubbles, and producing the effect denominated *effervescence*.

This is exactly what takes place when a bottle of champagne is uncorked : so long as the cork maintained the pressure, the gas previously absorbed by the liquid was retained ; but the moment the removal of the cork relieves the liquid from this pressure, the gas rises, and produces the sparkling effervescence with which everyone is familiar.

The same observations are applicable to other fermented liquors and gaseous drinks, such as soda water, effervescent lemonade, and so on.

A simple apparatus by which water charged with carbonic acid gas can be made is a common object of sale in the shops. This consists of a stone bottle, shown in *fig. 57*, a vertical section of it being given in *fig. 58*. The bottle is divided into two compartments, A and B, between which there is a communication by a capillary canal *a b* ; the substance which generates the gas is introduced through an opening *o* into an acid solution contained in A, after which the opening *o* is closed by a screw cover provided for the purpose. The upper compartment B of the bottle is previously filled with water to the point *a* ; a pipe *i* descends in it nearly to the bottom, and communicates with a lateral spout *v* ; that communication, however, being cut off when the screw *p* is turned, so that its end presses on the upper opening of the tube *i*. When the screw *p* is turned down, so as to shut off the communication between *i* and *v*, the carbonic acid generated in A rising through *b a*, collects in the upper part of the bottle ; and being pressed upon the surface of the water, is dissolved by it, and this goes on until the pressure of the

gas becomes so great as to retard or stop its generation in A. In all states of the gas the water B will contain as much of it as would occupy the space filled by the water if the water were absent.

When it is desired to obtain a draught of the liquid, a glass is held to the mouth of the tube *v* and the screw *p* is turned so



Fig. 57.

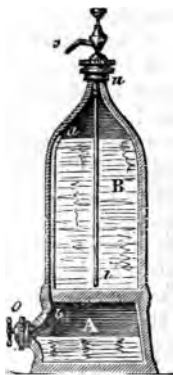


Fig. 58.

as to open the communication between *i* and *v*, when immediately the pressure of the gas in the bottle forces the water up the tube *i*, and through *v* into the glass. When the glass is filled, the screw *p* is closed, and the water in the glass being relieved from the excessive pressure to which it was subject in the bottle, the gas effervesces, and an effect is produced with which everyone is familiar.

170. **Thilorier's apparatus.**—The liquefaction and solidification of carbonic acid gas was first effected by M. Thilorier, by means of an apparatus, a vertical section of which is represented in *fig. 59*, where A and B are two strong metal cylinders, constructed so as to resist an enormous pressure: they are closed by screw stoppers, and communicate with each other by a small pipe *s t x*; stop-cocks are placed at *r* and *r'*, so as to open or close at pleasure the communication between the pipe *s t x* and either cylinder. The cylinder A is called the *generator*, and B the *receiver*.

These cylinders are constructed precisely alike, each containing about 2 gallons. The generator is suspended vertically between two points, *f* and *f'*, placed a little above its centre of gravity, on which it is capable of receiving a rocking motion.

Removing the stopper x from the generator, a gallon of water is introduced into it at a temperature of about 35° , with about 4 lbs. of bicarbonate of soda. A cylindrical copper tube $u v$

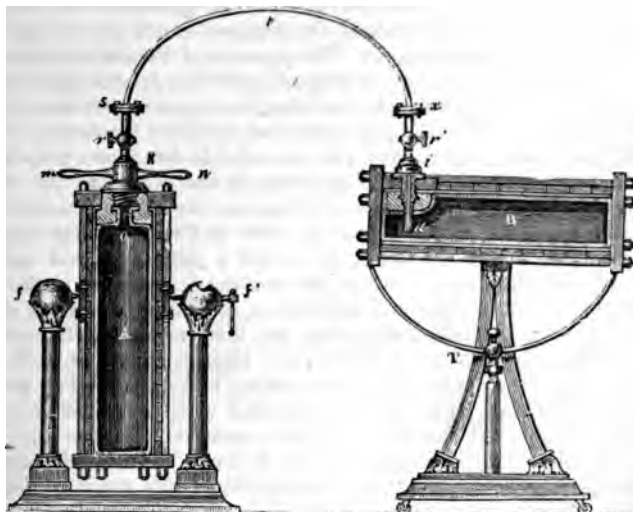


Fig. 59.

(fig. 6o), containing about 2 lbs. of concentrated sulphuric acid, is then introduced into the generator, and so placed as to be held always in the direction of its axis, so that when the generator is vertical, no part of the acid can fall from the tube. By turning the generator upon its supports until it is inclined a little beyond a horizontal position, the acid is all discharged from the tube, and mixes with the solution of the bicarbonate.

The top of the generator being previously closed by the handles *m n* and the stop-cock *r*, chemical action commences, and the sulphuric acid, acting upon the soda bicarbonate, liberates the carbonic acid, with which the upper part of the generator becomes immediately filled, and its condensation soon becomes so great as to exercise a pressure by which a part of the gas is liquefied in the generator. The tube *stx* being now screwed on, and the stop-cocks *r* and *r'* opened, the carbonic acid rushes in the gaseous state through the tube into the receiver *B*, where it is soon condensed, and assumes the liquid form. This condensation is produced partly by



Fig. 6o.

the pressure of the gas, and partly by the difference between the temperatures of the generator and receiver. By the action of the sulphuric acid on the water with which it is mixed the temperature of the solution and of the generator is about 35° , while the temperature of the receiver is not greater than that of the surrounding air. The pressure of the carbonic acid corresponding to the former temperature being 75 atmospheres, while that corresponding to the latter is only 50 atmospheres, a condensation must take place sufficient to reduce the density of the gas in the proportion of 3 to 2; so that in less than a minute all the carbonic acid of the generator is transferred to the receiver, after which the communications are closed, the generator refilled, and the process repeated. After this operation has been performed five or six times, about half a gallon of liquid carbonic acid will be collected in the receiver. Above the surface of this liquid is a gaseous atmosphere, exercising a pressure of about 50 atmospheres, supposing the temperature of the surrounding medium to be about 15° . It is evident that if the stop-cock *r'* be opened, the tube *a* being below the level of the liquid, the liquid acid will be projected with great force from the receiver. If the tube *stx* were detached, and the liquid were allowed to issue into the air, it would immediately take the gaseous form, producing a whitish cloud, like steam issuing from the valve of a high-pressure engine. Owing to the enormous quantity of heat rendered suddenly latent by the instantaneous conversion of the liquid acid into gas, the gas thus issuing would have an extremely low temperature. If, however, the jet of liquid acid be directed into a strong metallic flask, a portion of it only will be volatilised, taking from the sides of the flask the heat which renders it latent. By this means the temperature of the flask will be reduced to a temperature so low as -70° on Fahrenheit's scale. The acid reduced to this temperature will become solid, under the form of a white cotton, like snow. It can be preserved in this state much longer than in the liquid state; its evaporation being very slow, owing to its low conducting power in the solid form. An air thermometer surrounded with it would show a temperature of -108° , or 108° below zero, or 140° below the freezing point on Fahrenheit's scale.

A flake of this snowy substance can be placed upon the hand without producing any considerable sense of cold, because it is continually isolated from the hand, and the contact is prevented by a stratum of gas which is continually disengaged from it—an effect which has an obvious analogy to the phenomena manifested by liquids let fall upon red-hot iron, as already described. If,

however, instead of laying the acid flakes upon the hand, they are pressed between the fingers, a most painful sensation would be produced, like that attending a severe burn, and the skin will be blistered in the same manner.

The metallic box or flask in which the solid acid is usually collected is represented in *fig. 61*. It is composed of two parts $a b c d$, and $a' b' c' d'$ (*fig. 62*), which can be easily united or separated. The part $a b c d$ has a tube $c d$ leading to it, into which a small tube u enters, which has been previously fixed at x upon the receiver B (*fig. 59*). On opening the stop-cock r' , the liquid gas rushes out through u , and, passing through the tube

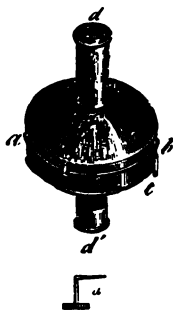


Fig. 61.

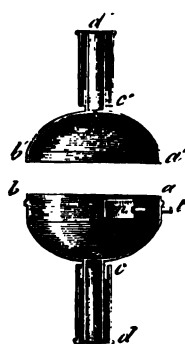


Fig. 62.

$d c$, penetrates into the box, where it is discharged tangentially from the point of the tube u , which is bent at right angles to $d c$. It strikes against a plate of metal m , so disposed as to produce a gyratory motion; a part of the liquid acid takes the form of gas, which, after whirling round the box, escapes at the central tubes $c d$ and $c' d'$; the remainder of the acid is solidified in the form already described of snowy flakes, and can be collected on opening the box. The tubes $c d$ and $c' d'$ are enveloped by two concentric tubes wrapped with cloth, so that the operator can hold them without suffering from the severe cold of the remainder of the box.

If a liquid which does not combine chemically with the carbonic acid, and which is not congealed at a very low temperature, be poured upon it, the evaporation of the acid is accelerated, because the liquid filling its pores increases considerably its conducting power.

The rapid evaporation thus effected produces a cold of extraordinary intensity, by means of which bodies immersed in the acid

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may be reduced to a temperature far below that of the solid acid. If such a mixture be placed under the receiver of an air pump, and the evaporation be further accelerated by making a vacuum around it, a temperature may be obtained which will be 100° below the freezing point.

The liquid commonly used for this purpose is ether. By means of the frigorific paste thus produced 2 lbs. of mercury may be easily solidified in a few minutes; and if a glass tube, hermetically sealed, containing liquid carbonic acid, be plunged in such a mixture, the acid will be immediately congealed, assuming the appearance of ice.

A most convenient apparatus for the liquefaction and solidification of carbonic acid on a large scale has been recently con-



Fig. 63.

structed by Messrs. Deleuil, of Paris. This apparatus is represented in *fig. 63*. It consists of two cylinders, perfectly equal and similar, and similarly suspended. They are in cast iron, about $1\frac{1}{2}$ inch thick, and having a capacity of something less than a gallon. They are strongly bound with four longitudinal ribs and three hoops of wrought iron. The arrangement of stop-

cocks and other communications corresponds with that in Thilorier's apparatus already described.

171. Faraday's Method of liquefying Gases.—Humphrey Davy and Faraday were the first to liquefy gases which were considered permanent up to that time. Faraday especially devoted himself to systematic experiments on the subject, by a method as simple as it is effective. The apparatus consists of a very strong bent glass tube, one end of which contains chemical substances which evolve the gas on the application of heat, while the other end is immersed in a freezing mixture. The large quantity of gas evolved is contained in a confined space, and this increase of pressure, combined with the lowering of temperature by means of the freezing mixture, produces liquefaction, and the liquid accordingly collects in the cold portion of the tube. Cyanogen may thus be liquefied by heating cyanide of silver, enclosed in one end of the tube; and sulphuretted hydrogen by using the bisulphide of hydrogen, a heavy yellow oily liquid.

In the same or a similar manner the following gases have been liquefied: sulphurous acid, chlorine, ammonia, hydrochloric acid gas, carbonic acid, and several other gases. In his later experiments Faraday employed two pumps, the first having a piston of an inch, and the second of only half an inch diameter. The first pump in the earlier stage of the operation forced the gas through the second in the receiver. In the later stage the second pump was also worked, so as to force the gas already condensed to 10, 15 or 20 atmospheres into the receiver at a much higher pressure. The receiver was a tube of green bottle-glass, and was immersed in a very intense freezing mixture, consisting of solid carbonic acid and ether, the cooling effect being sometimes increased by exhausting the air and vapour from the vessel containing the freezing mixture, so as to promote more rapid evaporation.

172. Experiments of Cagniard de la Tour, Drion, and Andrews.—Cagniard de la Tour obtained remarkable results by heating volatile liquids, such as alcohol, petroleum, and sulphuric ether, in closed glass tubes of great resisting power, the capacity of the tubes being about double the volume of the enclosed liquid. At a certain temperature, which was 36°C . for alcohol, and 42° for ether, the liquid suddenly disappeared, being apparently converted into vapour in an instant.

Drion made similar experiments on hyponitric acid, sulphurous acid, and hydrochloric ether, and his results may be embodied in the following statements:—1st, the coefficients of

apparent expansion of these liquids increase rapidly with the temperature. 2nd, their coefficients of apparent expansion become equal to the coefficient of expansion of air at temperatures much lower than those at which total conversion into vapour occurs. 3rd, their coefficients of apparent expansion may even become double and more than double the coefficient of expansion of air.

Thilorier had already shown that the expansion of liquid carbonic acid between the temperatures 0° and 30° C. is four times as great as that of air. Drion found that at 130° C. the coefficient of expansion of sulphurous acid was $\cdot 009571$. He also observed that when the temperature was raised very gradually to the point of total vaporisation, the free surface lost its definition and was replaced by a nebulous zone without definite edges, and the reflecting power had disappeared also. This zone increased in size both upwards and downwards, but at the same time became less visible until the tube appeared completely empty. The same appearances were reproduced in inverse order on gradually cooling the tube. When the liquid was contained in a capillary tube, or when a capillary tube was partly immersed in it, the curvature of the meniscus and the capillary elevation decreased as the temperature rose, until finally, just before the occurrence of total vaporisation, the surface became plane, and the level was the same within as without the tube.

The experiments of Dr. Andrews, who used an apparatus which permitted the pressure and temperature to be altered independently of each other, have proved that carbonic acid cannot be liquefied at temperatures above 31° C. When at a temperature above 31° the gas is subjected to intense pressure, it becomes reduced to a condition in which, though homogeneous, *it is neither a liquid nor a gas*. When it is in this condition, and the temperature be lowered while the pressure remains constant, it is reduced to the liquid state; again, being in that condition, and the pressure being lowered while the temperature remains constant, it is converted into a gas. In neither case, however, during the transition, can any breach of continuity be detected. When carbonic acid is at temperatures below 31° , it remains completely gaseous until the pressure reaches a certain limit depending on the temperature, and at any pressure which exceeds this limit, liquefaction commences and continues until the whole of the gas is liquefied, the boundary between the liquefied and unliquefied portions being always sharply defined. The temperature of 31° C. has been

called the *critical temperature* for carbonic acid. Other substances, for example, nitrous oxide, hydrochloric acid, ammonia, sulphuric ether, and carbon sulphide, have exhibited critical temperatures, which for some of these substances were above 100° C. It is probable, that every other substance, whether it is a liquid or a gas, under ordinary circumstances, has in like manner its own critical temperature.

In order to convert *continuously* a gas into a liquid, the gas must first be compressed at a temperature higher than its critical temperature until it is reduced to the volume which it will occupy when liquid, and then it must be cooled below the critical temperature. In order to convert continuously a liquid into a gas, its temperature must be raised first above the critical point under a pressure sufficient to prevent ebullition, and then it must be allowed to expand.

When a substance is a little above its critical temperature and occupies a volume which would, at a lower temperature, be compatible with partial liquefaction, very great changes of volume are produced by very slight changes of pressure. On the other hand, when a substance is at a temperature a little below its critical point, and is partially liquefied, a slight increase of temperature leads to a gradual obliteration of the surface of demarcation between the liquid and the gas; and when the whole has thus been reduced to a homogeneous fluid, it can be made to exhibit an appearance of moving or flickering *striae* throughout its entire mass by slightly lowering the temperature, or suddenly diminishing the pressure.

The apparatus employed in these remarkable experiments is described in the *Philosophical Transactions* for 1869.

173. Exceptions from the general law.—It has been found that when gases are submitted to extreme compression, and deprived of a large portion of their heat, they begin to depart from the general law in virtue of which the density of gaseous bodies at the same temperature is proportional to the compressing force, and they are found to acquire a density greater than that which they would have under this general law. This would appear, therefore, as a departure from the law, preliminary to the final change from the gaseous to the liquid state; and, in this point of view, analogies have been observed which render it probable that the point of condensation of several of the gases not yet liquefied has been very nearly approached.

Thus, it has been found that the density of several of them, among which may be mentioned light carburetted hydrogen (marsh gas) and olefiant gas (heavy carburetted hydrogen), has

been sensibly greater than that due to the compressing force under extreme degrees of compression. Of these two gases the latter has indeed been liquefied under an enormous pressure at a temperature of -110°C .

174. *Ebullition.*—If heat be continually imparted to a liquid, its temperature will be augmented, but will only rise to a certain point on the thermometric scale. At that point it will remain stationary, until the whole of the liquid shall be converted into vapour. During this process, vapour will be formed in greater or less quantity throughout the entire volume of the liquid, but more abundantly at those parts to which the heat is applied. Thus if, as usually happens, the heat be applied at the bottom of the vessel containing the liquid, the vapour will be formed there in large bubbles, and will rise to the surface, producing that agitation of the liquid which has been called *boiling or ebullition*.

This limiting temperature is called the *boiling point* of the liquid.

Different liquids boil at different temperatures. The *boiling point* of a liquid is therefore one of its specific physical characters.

175. *The boiling point depends on pressure.*—Liquids in general being boiled in open vessels are subject to the pressure of the atmosphere. If this pressure vary, as it does at different times and places, or if it be increased or diminished by artificial means, the boiling point will undergo a corresponding change. It will rise on the thermometric scale as the pressure to which the liquid is subject is increased, and will fall as that pressure is diminished.

The boiling point of water is 212° on Fahrenheit's scale, when subject to a pressure very nearly equal to that of a column of 30 inches of mercury. It is 185° , when subject to a pressure expressed by 17 inches of mercury.

In general, the temperatures at which water would boil under the pressures expressed in the second column of the table (page 165), are expressed in the first column.

176. *Experimental verification.*—Let water at the temperature of 90° , for example, be placed in a glass vessel, under the receiver of an air-pump, and let the air be gradually withdrawn. After a few strokes of the pump the water will boil; and if the gauge of the pump be observed, it will be found that the height of the mercurial column will be about $23\frac{1}{2}$ inches. Thus, the pressure to which the water is submitted has been reduced from the ordinary pressure of the atmosphere, to a diminished pressure expressed by $23\frac{1}{2}$ inches, and we find that the temperature at which the water boils has been lowered from 100° to 90° . Let

the same experiment be repeated with water at the temperature of 80° , and it will be found that a further rarefaction of the air is necessary, but the water will at length boil. If the gauge of the pump be now observed, it will be found to stand at 15 inches, showing that at the temperature of 80° water will boil under half the ordinary pressure of the atmosphere. This experiment may be varied and repeated, and it will always be found that water will boil at that temperature which corresponds to the pressure given in the tables already referred to.

The dependence of the boiling point on the pressure may also be illustrated by the following simple experiment. In a glass flask water is boiled for some time, until it may be assumed that all the air is expelled by the steam. The flask is then quickly removed from the source of heat, closed by a cork, and placed in an inverted position upon a suitable support. If now the bottom of the flask be cooled by pouring upon it some cold water, the water within the flask will begin to boil again. The cause of this is the condensation of a portion of the steam above the surface of the water in the flask, and a consequent rapid diminution of the pressure; the boiling point of the water is thus lowered, and ebullition takes place under the diminished pressure at a temperature below 100° .

A most important and useful application of the principle, that under feeble pressures evaporation proceeds at an increased rate, has been made in the use of the 'air-pump' for concentrating solutions, which either cannot bear a high degree of heat without becoming decomposed or suffering deterioration, or which can be more cheaply evaporated in an exhausted space. Thus in the manufacture of sugar the syrup is enclosed in an air-tight vessel which is exhausted by a steam-engine. The evaporation consequently goes on at a lower temperature, which secures the syrup from injury. The same method is employed in evaporating the juice of certain plants used in preparing medicinal extracts.

The influence of pressure on ebullition may be further illustrated by means of the apparatus usually called a *pulse-hammer*. It consists of two glass bulbs, joined by a tube of smaller dimensions, very similar to the bulbs A and B and the tube joining them, represented in *fig. 17*, page 32. The apparatus is partly filled with coloured spirit of wine, which has been boiled in it so as to expel the air through a small aperture which was closed after the air had been expelled; there is then a vacuum in the apparatus, or rather a pressure due to the tension of vapour of alcohol at the ordinary temperature, which

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is under these circumstances very small. Consequently if the instrument is held with the bulbs upwards, in a horizontal position, and one of the bulbs placed in the hand, the heat of the hand is sufficient to produce incipient ebullition and a tension which drives the liquid into the other bulb, and, as the ebullition of the liquid is not retarded by any appreciable superincumbent pressure, it boils briskly.

177. Influence of altitude.—It is well known that, as we ascend in the atmosphere, the pressure is diminished in consequence of the quantity of air we leave below us, and that, consequently, the barometer falls. It follows, therefore, that at stations at different heights in the atmosphere, water will boil at different temperatures; and that the boiling point at any given place must therefore depend on the elevation of that place above the surface of the sea. Hence the boiling point of water becomes an indication of the height of the station, or, in other words, an indication of the atmospheric pressure, and thus the thermometer serves in some degree the purposes of a barometer.

In the following table the various temperatures, on Fahrenheit's scale, are shown at which the water boils in the different places therein indicated :—

Table of the Boiling Points of Water at different Elevations above the Level of the Sea.

Names of Places	Above Level of Sea	Mean Height of Barometer	Thermometer
	Feet.	Inches.	Degrees.
Farm of Antisana	13455	17·87	187·3
Town of Micuipampa (Peru) . . .	11870	19·02	190·2
Quito	9541	20·75	194·2
Town of Caxamarca (Peru) . . .	9384	20·91	194·5
Santa Fé de Bogota	8731	21·42	195·6
Cuenca (Quito)	8639	21·50	195·8
Mexico	7471	22·52	198·1
Hospice of St. Gothard	6808	23·07	199·2
St. Veran (Maritime Alps) . . .	6693	23·15	199·4
Breuil (Valley of Mont Cervin). .	6585	23·27	199·6
Maurin (Lower Alps)	6240	23·58	200·3
St. Rémi	5265	24·45	202·1
Heas (Pyrenees)	4807	24·88	202·8
Gavanne (Pyrenees)	4738	24·96	203·0
Briançon	4285	25·39	203·9
Baréges (Pyrenees)	4164	25·51	204·1
Palace of San Ildefonso (Spain). .	3790	25·87	204·8
Baths of Mont d'Or (Auvergne) .	3412	26·26	205·7
Pontarlier	2717	26·97	206·8

Table of the Boiling Points—continued.

Names of Places	Above Level of Sea	Mean Height of Barometer	Thermo- meter.
	Feet	Inches	Degrees
Madrid	1995	27·72	208·0
Innsbruck	1857	27·87	208·4
Munich	1765	27·95	208·6
Lausanne	1663	28·08	208·9
Augsburg	1558	28·19	209·1
Salzburg	1483	28·27	209·1
Neuchâtel	1437	28·31	209·3
Plombières	1381	28·39	209·3
Clermont-Ferrand (Préfecture)	1348	28·43	209·3
Geneva and Friburg	1221	28·54	209·5
Ulm	1211	28·58	209·7
Ratisbon	1188	28·58	209·7
Moscow	984	28·82	210·2
Gotha	935	28·86	210·2
Turin	755	29·06	210·4
Dijon	712	29·14	210·6
Prague	587	29·25	210·7
Mâcon (Saône)	551	29·29	210·9
Lyons (Rhône)	532	29·33	210·9
Cassel	518	29·33	210·9
Göttingen	440	29·41	211·1
Vienna (Danube)	436	29·41	211·1
Milan (Botanic Garden)	420	29·45	211·1
Bologna	397	29·49	211·1
Parma	305	29·57	211·3
Dresden	295	29·61	211·3
Paris (Royal Observatory, first floor)	213	29·69	211·5
Rome (Capitol)	151	29·76	211·6
Berlin	131	29·76	211·6

It follows from this connection between the boiling point of water and the pressure that the heights of mountains may be determined by observations made with the thermometer instead of with the barometer. Thus, let us suppose that water is boiled in a vessel at the foot of a mountain and also on its summit, and that the temperature of the boiling point is found to be t degrees at the base, and t' degrees at the highest point of the mountain. We know that the tension of the vapour of a boiling liquid is equal to the pressure upon the liquid; that is, to the pressure of the atmosphere in these cases; but the tension of the vapour, corresponding to the two temperatures t and t' , has been experimentally determined, and may be taken from Table I., page 167. Accordingly the tensions correspond-

ing to these two temperatures represent the atmospheric pressures at the two places ; that is, the heights of the barometer at the two localities ; and from these the height of the mountain may be calculated in the manner shown in the treatise on HYDROSTATICS in this series, page 147.

Roughly speaking, an ascent of about 1,080 feet lowers the boiling point of water by 1°C .

Special instruments are usually constructed for determining heights by the thermometer ; they are called *hypsometers* or *thermo-barometers*. Wollaston was the first to construct a thermo-barometer. The scale of his instrument extended only through three degrees, but each degree had a length of five centimetres. Regnault's hypsometer consists of a little boiler heated by a spirit lamp, and terminating in a telescope tube with an opening at the side through which the steam escapes. A thermometer dips into the steam and projects through the top of the tube so as to allow the temperature of ebullition to be read. This temperature, as already explained, gives at once the atmospheric pressure by reference to a table of vapour tensions, and the subsequent computations for determining the difference in altitude of two stations are the same as when a barometer is employed. For obtaining an approximate result, or where no great accuracy is required, it may be assumed that the height above the level of the sea is proportional to the difference of the observed boiling point at the higher station and 100° . In this case the height may be calculated from the formula—

$$\text{Height in metres} = 295 (100 - t) ;$$

Or,

$$\text{Height in feet} = 538 (212 - \theta) ;$$

where t is the observed temperature of the boiling point in centigrade, and θ in Fahrenheit's degrees.

Thus the boiling point in Quito (see preceding table) was found to be $195^{\circ}\cdot 8$, and its elevation of the sea level is 8,639 feet. By the formula just given we obtain—

$$\text{Height} = 538 (212 - 195\cdot 8) = 8,716 \text{ feet,}$$

which is a comparatively close approximation to the actual altitude.

178.—**Laws of Ebullition.**—From the preceding experimental facts the following general laws may be deduced, which regulate the physical phenomena accompanying ebullition.

I. *At the ordinary pressure of the atmosphere ebullition commences for each liquid at a definite temperature, which for the same liquid increases as the pressure increases.*

II. *Under ordinary circumstances the temperature during ebullition remains constant if the pressure remains the same.*

III. *The tension of the vapour given off during ebullition is equal to the pressure upon the liquid.*

It follows at once from the first of these laws, which is analogous to the first law of fusion (art. 120, page 129), that the boiling point of a liquid, if once determined at a definite pressure, constitutes a special physical characteristic of the substance which enables us to recognise it and to distinguish it from other bodies.

In the following table the *temperature of the boiling point* is that temperature at which the tension of the vapour formed during ebullition is equal to the normal atmospheric pressure of 760 millimetres.

Table of Boiling Points.

Substance	Temperatures of Boiling Point	Observer
Carbonic acid . . .	- 82°0	Faraday
Sulphurous acid . . .	- 10°0	Bussy
Ethylic chloride . . .	+ 11°0	Thénard
Ethylic nitrate . . .	21°0	Dumas
Aldehyde	20°8	Kopp
Hydrocyanic acid . . .	26°5	Gay-Lussac
Ether	34°9	Kopp
Methylic sulphide . . .	41°0	Regnault
Bisulphide of carbon . .	46°8	Marx
Bromine	59°6	Mitscherlich
Carbon chloride	60°8	Liebig
Chloroform	62°0	„
Methyl alcohol	65°5	Kopp
Nitric acid	66°0	Dumas
Ethylic oxide	73°0	Regnault
Common alcohol	78°4	Kopp
Benzene	80°4	„
Chloral	94°0	Dumas

Table of Boiling Points—continued.

Substance	Temperature of Boiling Point	Observer
Water (distilled)	100°	Dumas
Formic acid	100°	Kopp
Acetic acid	117°3	„
Potassium chloride . . .	120°	Regnault
Tin chloride	120°	Dumas
Valerianic acid	132°	Otto
Butyric acid	157°	Kopp
Amylen	160°	Cahours
Turpentine	160°	—
Iodine	175°	Dumas
Oxalic ether	184°	„
Naphthaline	212°	„
Benzoic acid	245°	Mitscherlich
Petroleum	280°	Boussingault
Common sulphuric acid . .	288°	Davy
Phosphorus	290°	Mitscherlich
Sulphur	316°	„
Linseed oil	316°	Murray
Strong sulphuric acid . .	325°	—
Mercury	350°	Dulong
Cadmium	860°	—
Zinc	1040°	—

179. **Causes which modify the temperature of the boiling point.**—The boiling point of a liquid is influenced by several other causes independent of the pressure. The principal of these causes are : the nature and quality of substances dissolved in the liquid, and the nature of the vessel in which the ebullition takes place.

The boiling point is not influenced by substances which are

only mechanically suspended in the liquid. But if any substance is chemically *dissolved* in a liquid, the boiling point of the solution is in general raised. Thus the addition of any soluble salt raises the boiling point of water. The vapour, however, which rises from such solutions consists of pure water, and its temperature corresponds to that of the boiling point of pure water.

Legrand has made experiments on the temperature of the boiling point of saturated aqueous solutions of various salts, the results of which are given in the following table :—

Name of Salt dissolved.	Boiling Point	Quantity of Salt which saturates 100 Parts of Water
Potassium chlorate . . .	104.2	Parts 61.5
Barium chloride . . .	104.4	60.1
Sodium carbonate . . .	104.6	48.5
Sodium phosphate . . .	106.5	113.2
Potassium chloride . . .	108.3	59.1
Sodium chloride . . .	108.4	41.2
Ammonium chloride . . .	114.2	88.9
Neutral potassium tartrate .	114.67	269.2
Potassium nitrate . . .	115.9	335.1
Strontium chloride . . .	117.6	117.5
Sodium nitrate . . .	121.0	224.8
Sodium acetate . . .	124.37	209.0
Potassium carbonate . . .	133.0	205.0
Calcium nitrate . . .	151.0	362.2
Potassium acetate . . .	169.0	798.2
Calcium chloride . . .	179.5	325.2

Legrand has further determined the quantity of various salts, which must be added to 100 parts of water, so that the boiling point may be raised by 1, 2, &c., degrees. The following are the principal results :—

[illegible]

24	354.0	86.0	165.1	172.2	147.1	204.5
26	396.0	92.2	180.1	184.5	157.3	
28	440.2	98.4	196.1	197.0	167.7	
30	487.4	104.6	213.0	209.5	178.1	
32	537.3	110.9	230.6	222.2	188.8	
34	590.0	117.2	248.7	235.1	199.6	
36	645.0	123.5	267.5	248.1		
38	705.5	129.9	287.3	261.3		
40	770.5	136.3	308.3	274.7		
42	840.6	142.8	330.8	288.4		
44	915.5	149.4	354.9	302.6		
46	995.5	156.2	380.6	317.4		
48	1081.5	163.2	407.9	333.2		
50	1173.5	170.5	436.9	357.2		
52	1273.0	178.1	467.6			
54	1383.0	186.0	500.0			
56	1504.0	194.3	534.1			
58	1637.0	203.0	569.9			
60	1775.0	212.1	607.4			
62	1923.0	221.6	646.6			
64	2084.0	231.5	687.6			
66	"	241.9	730.4			
68	"	252.8	775.0			
70	"	264.2				
72	"	276.1				
74	"	288.5				
76	"	301.4				
78	"	314.8				
80	infin.					

In general we may derive the following facts from the preceding tables : First, the ebullition of water is the more retarded the greater the quantity of the dissolved substance ; second, each dissolved substance differs in its effect from every other substance that may be dissolved in the same liquid.

Analogous results are obtained with respect to the boiling point of water which contains acids in solution. With liquid mixtures we have the following facts experimentally ascertained. If two liquids are placed together in a vessel and boiled, we must distinguish the two cases, when the liquids physically intermix with one another or not. In the latter case, when the more volatile liquid is on the top of the less volatile, the upper liquid will begin to boil at its own boiling point. But if the more volatile liquid is the heavier of the two and thus remains below, the remarkable fact is observed that the more volatile liquid begins to boil at a lower temperature than its ordinary boiling point. If, for example, a quantity of carbon disulphide be heated in a flask, in a water bath, to a temperature of $43^{\circ}5$, and then poured into the water in the bath, a brisk ebullition of the carbon disulphide will be observed, although its ordinary boiling point is $46^{\circ}8$. It appears that in this case the tension of the carbon disulphide vapour at $43^{\circ}5$ being 696 millimetres, and that of aqueous vapour at the same temperature 64 millimetres, the tension of both together is 760 millimetres, and that for the ebullition of the more volatile liquid it is sufficient that the combined tension of both vapours be equal to that of the atmosphere.

If the liquids are capable of forming a physical mixture when brought together, then the boiling point, as well as the tension of the vapour formed, depends on the ratio of the two liquids, and may not only vary between the lower boiling point and the higher one, but may even exceed the latter. But here also the ratio of the pressure under which ebullition commences bears a nearly constant ratio to the sum of the two pressures corresponding to the boiling points of each liquid contained in the mixture.

180. **Rudberg's law.**—*Rudberg* has established a remarkable law with reference to the influence of substances in solution upon the temperature of the boiling point. It may be enunciated thus : *Whatever may be the temperature of the boiling solution, the temperature of the aqueous vapour generated by the liquid is always equal to the temperature of the aqueous vapour which would be generated by pure water boiling under the same pressure.* Under a pressure of 760 millimetres the temperature

of the aqueous vapour, which rises from a saline solution boiling at a considerably higher temperature, is thus not higher than 100° . Regnault caused a solution of calcium chloride to boil in an artificial atmosphere, of which the pressure was made to change from 82.52 to $3,122.69$ millimetres. The temperature of the boiling solution rose under these circumstances from 52° to $147^{\circ}91$, while the temperature of the issuing vapour rose from $47^{\circ}84$ to $145^{\circ}57$; very nearly the same as if the liquid had been pure water, in which case the two latter temperatures were found to be $47^{\circ}84$ and $145^{\circ}0$ at the two pressures mentioned.

Regnault saw the explanation of this behaviour of the vapour in the condensation which takes place upon the stem of the thermometer. Since pure water is deposited upon the stem, the vapour surrounding it being the source of the condensed water, the temperature of the vapour cannot well exceed that of the condensed water. Although the bubbles of vapour are at a higher temperature as long as they are within the liquid and therefore in a non-saturated (superheated) and expanded state, they rapidly alter when out of the liquid and their temperature falls to 100° . Regnault, Magnus, and Wüllner have finally expressed the general opinions from their experiments, that no conclusion with reference to the temperature of the surrounding vapour can be drawn from the indications of the thermometer.

Magnus has demonstrated by direct experiment that the aqueous vapour given off by a boiling saline solution leaves the liquid with the temperature of the latter, and is therefore in a non-saturated (superheated) state. The apparatus, of which *fig. 64* shows a section, had an interior vessel, *A*; into the liquid contained in *A* a thermometer *a* was introduced, and the temperature of the boiling liquid could thus easily be read. The vapour generated in *A* passed through the opening *a* into a tube *B*, which contained a thermometer *b*. The temperature of the vapour when it arrived in the vessel *B* could thus also be read externally. The whole was surrounded by another vessel *C*, which acted like the

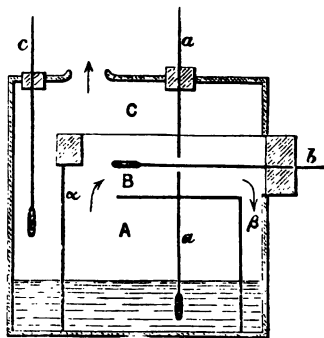


Fig. 64.

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jacket *a* in *fig. 4*, page 14, protecting the interior by a layer of steam from contact with the external air, and permitting at the same time free egress to the steam. The steam passed from *b* to *c* through β , and rapid cooling was thus entirely prevented. The following temperatures were observed with *a* and *b* :—

	<i>a</i>	<i>b</i>	<i>a</i> - <i>b</i>
Chloride of calcium .	$\overset{\circ}{107\cdot0}$ 116 \cdot 0	$\overset{\circ}{105\cdot25}$ 111 \cdot 2	$\overset{\circ}{1\cdot75}$ 4 \cdot 8
Nitrate of potassium .	107 \cdot 7 117 \cdot 0	105 \cdot 2 111 \cdot 0	2 \cdot 5 6 \cdot 0
Nitrate of sodium .	107 \cdot 6 116 \cdot 0	106 \cdot 2 108 \cdot 7	1 \cdot 4 7 \cdot 3

There is thus a gradual transition from the temperature of the boiling saline liquid to a temperature nearer to the boiling point of pure water.

181. **Babo's and Wüllner's experiments.**—The high boiling point of saline solutions is most probably a consequence of the attraction between the liquid and the saline particles dissolved in it; an attraction which is frequently observed even at ordinary temperatures in many saline substances which absorb moisture very freely. Connected with this phenomenon is further the fact, that the *elastic force* of the vapour given off by saline solutions is always less than the tension of vapour given off by pure water under circumstances which are in all other respects precisely the same.

Gay-Lussac had already shown that the tension of the vapour given off by a solution of common salt (sodic chloride) diminished when the solution was made stronger; that is, when its density increased.

Thus he found the following corresponding vapour tensions and densities :—

Density of Solution.	Vapour Tension.
1 \cdot 000	1 \cdot 000
1 \cdot 096	0 \cdot 906
1 \cdot 063	0 \cdot 823
1 \cdot 205	0 \cdot 753

Babo instituted on the subject a series of systematic experiments by using vapour barometers, which vaporised above the mercurial column saline solutions of various strengths, and which permitted the measurement of the vapour tensions at different temperatures. For a solution of chloride of calcium, for example, of which the boiling point was 110° , he found the results stated in the following table, which gives the temperature in the first column ; the corresponding tension of the vapour given off by the saline solution in the second column ; the tension of vapour given off by pure water at the same temperature in the third ; and, finally, in the fourth column the quotient obtained by dividing the values in the second column by the corresponding one in the third.

Temperature	Tension of Vapours formed		Quotient
	Above Chloride of Calcium	Above Water	
	Millimetres	Millimetres	
19 C.	9.0	16.3	0.55
35	26.8	41.8	0.641
59	92.8	141.8	0.654
65	121.6	186.6	0.652
78	212.0	326.8	0.645
			Mean : 0.648

It appears from this, and generally from the whole of the experiments, that the quotients thus obtained are very nearly (except the first in the above table) equal to one another, and that the tension of vapour given off by a saline solution bears a constant ratio to the tension of the vapour given off at the same temperature by pure water. These ratios were, however, found to differ with each particular substance in solution, and also with the quantity of the dissolved salt.

Wüllner experimented on a number of saline solutions with the following result. If T denotes the tension of vapour formed by a saline solution at a certain temperature, and T_w the corresponding tension of the vapour formed by pure water, then T is less than T_w by a quantity which is nearly proportional to T_w , to the quantity of salt contained in the liquid (n parts of salt in 100 parts of water), and to a co-efficient a which depends

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on the nature of the substance. His results may be more accurately expressed by the formula :—

$$T = T_w(1 - \alpha n - \beta n T_w),$$

in which the co-efficients α and β are the following for the substances named :—

Substance	α	β
Chloride of sodium . . .	0·00601	—
Sulphate of sodium . . .	0·00236	—
Nitrate of sodium . . .	0·00315	+ 0·000000907
Chloride of potassium . . .	0·00390	+ 0·000000538
Sulphate of potassium . . .	0·00383	— 0·00000190
Nitrate of potassium . . .	0·00196	+ 0·00000108
Cane sugar . . .	0·00074	— 0·00000012
Sulphuric acid . . .	0·03761	—

If two salts are contained in a solution, and their quantities are in a definite proportion, the diminution of vapour tension will also increase with the total quantity of the solid salts present ; but the decrease is entirely depending on the *ratio* of the quantities and does not correspond with the sum of the individual effects of each substance.

Sulphuric anhydride acts in this respect like any soluble salt. Regnault mixed one equivalent of the anhydride ($\text{SO}_3 = 80$) with varying equivalents of water ($\text{H}_2\text{O} = 18$), and found the following ratios of the vapour tensions, the tensions being denoted as above :—

Sulphuric Anhydride	Water	Ratio $\frac{T}{T_w}$
(Equivalents)	(Equivalents)	
1	infin.	1·00
1	18	0·84
1	12	0·70
1	10	0·63
1	8	0·49
1	6	0·33
1	5	0·21
1	4	0·13
1	3	0·06
1	2	0·00

Thus a mixture of one equivalent of the anhydride with two of water bears no pressure of vapour. Salts with great affinity for water behave similarly, and substances of this kind, like chloride of calcium, are employed for the purpose of drying gases, either by introducing them into the space containing the gas, or by placing them into tubes through which the gas to be dried is made to flow.

182. The temperature of the boiling liquid.—Influence of vessel.—A liquid which is contained in an open vessel is, as is well known, by the combined application of heat gradually changed into vapour, which is dissipated in the surrounding atmosphere. At first this action is confined to the surface, but after some time bubbles of vapour are formed in the interior of the liquid; these rise to the top, and set the whole mass in motion, with more or less vehemence, accompanied by a characteristic noise. This is essentially in what ebullition or boiling consists. If the gradual progress of this phenomenon be observed—for example, if water be boiled in a glass flask—it will be seen that at a certain time after the commencement of the experiment minute bubbles make their appearance; these are bubbles of air, which was dissolved in the water. Next, larger bubbles are formed at the bottom of the vessel, and at those parts of the sides which are most immediately exposed to the action of the fire. These bubbles ascend, decrease in volume as they rise, and disappear before reaching the surface. This stage is accompanied by a characteristic sound, called the *singing* of the liquid. The sound is most probably produced by the collapsing of the bubbles as they are condensed by the colder water through which they pass. Finally, the bubbles increase in number, growing also larger as they ascend, until they burst at the surface, which is thus kept in a state of agitation. The liquid is then said to boil.

Although the temperature of the vapour thus formed while the liquid boils, provided its cooling be prevented, is always constant, and corresponds to that of saturated vapour at that particular pressure at which the liquid is boiled; yet experience shows that the temperature of the liquid itself is by no means constant, but is subject to variations which may amount to several degrees. In the beginning the lower portions of the liquid, that is, those nearer to the source of heat, are hotter than those above them. This is clearly shown by the condensation of the bubbles of vapour formed at the bottom when they reach the upper layers. Moreover, in order to produce a bubble of vapour in the interior of the liquid, the heat applied has not

only to overcome the external pressure, but also the cohesion of the liquid particles, and at the sides of the vessel also the adhesion between the liquid and the wall. But while in the interior of the liquid the molecular forces act equally all round, this is not the case at the points where liquid and vessel are in contact; here the temperature is also somewhat higher than in the interior, hence the formation of bubbles takes place principally upon the walls. Metal vessels transmit the effect of heat with considerable ease, hence liquids boil at a lower temperature in metal vessels than in those made of china or glass, although the difference amounts to not more than 1° or $1^{\circ}5$.

Gay-Lussac was the first to make accurate observations on this point. He found that whatever the form or size of a metal vessel, water boiled in it at 100° , while in a clean glass vessel the thermometer showed the temperature of boiling water as $101^{\circ}23$. If powdered glass was thrown into the glass vessel, the temperature of the boiling liquid was $100^{\circ}23$, but if metal filings were thrown in, the thermometer indicated 100° . Munke and Rudberg confirmed these facts. The latter found the temperature of boiling water in an iron vessel $1^{\circ}3$ lower than in a glass vessel, and Munke found that in vessels of different metals, and also in different glass vessels, the temperatures were different. *Marcet* made afterwards more precise experiments, and found that the temperature of a boiling liquid varies very appreciably in different vessels, according to the degree of adhesion of the liquid and the substance of the vessel. The greater this adhesion the higher is the temperature of the boiling liquid. *Marcet* covered the interior of a glass flask, in which the temperature of boiling water was $101^{\circ}2$, with a thin film of sulphur, thus diminishing the adhesion; the temperature of the liquid boiling in the flask was now found $99^{\circ}85$. Another vessel, in which water boiled ordinarily at 101° , was carefully cleaned inside with concentrated sulphuric acid, and rinsed with hot water until no trace of the acid was left within. Pure distilled water boiling in this flask had a temperature of between 105° and 106° . The same result was obtained by treating another flask in the same manner with caustic potash. The temperature of the boiling water was raised to 103° . Now as the effect of the acid and the potash is to clean the glass thoroughly, and the adhesion between water and clean glass is greater than that between water and glass which is not quite clean, the temperature of the boiling liquid was in both cases raised by increasing the adhesion. *Marcet* found the same result with other liquids. Thus alcohol of specific gravity

0·801, boiled in a metal vessel, had a temperature of $78^{\circ}\cdot 5$, but when boiled in a glass flask the temperature was $79^{\circ}\cdot 2$.

183. **Influence of dissolved air.**—*Donny* was the first to show that water may be heated in clean glass vessels far beyond the ordinary boiling point, if previously care be taken to expel the dissolved air as much as possible. He took a glass tube, bent twice and terminated at one of its extremities by a series of bulbs. In order to remove the solid particles adhering to the sides which always detain portions of air, the tube is carefully washed out with alcohol and ether, and afterwards with dilute sulphuric acid. Water is then introduced and boiled long enough to expel the air dissolved in it, and while ebullition is proceeding the end of the apparatus is hermetically sealed. The other extremity is now plunged in a strong solution of chloride of calcium, which has a very high boiling point, and the tube is so placed that all the water shall lie in this extremity; it will then be found that the temperature may be raised to 135° without producing ebullition. At about this temperature bubbles of steam are seen to be formed, and the entire liquid mass is thrown forward with great violence. The bulbs at the end of the tube are intended to diminish the shock thus produced.

That water freed from dissolved air may be heated to a temperature far higher than the ordinary boiling point—and the higher above it the more the absorbed air has been removed—has afterwards been proved by the more extended experiments of *Dufour*. In one series of experiments *Dufour* took advantage of the principle that the boiling point of water is lowered by a diminution of pressure, and that to a definite pressure corresponds at the same time a definite boiling point. Accordingly if a vessel containing water at 100° be placed under the receiver of an air-pump and the air partly exhausted, the pressure will be diminished, and boiling will recommence at some temperature below 100° , to which the water has in the mean time cooled. But the lower temperature and the lower pressure are intimately connected, so that when a certain amount of air is left in the receiver, and the cooling proceeds to a definite temperature, the boiling will cease at that temperature. If a further amount of air is removed, boiling will begin again when a certain lower pressure is reached, and so on. In *fig. 65* *A* is a flask in which water is made to boil, and the thermometer *a* indicates the temperature. The flask *A* is connected with a condensing vessel *B* by the tube *b*, and finally with the air-pump by the tube *c*. A gauge in the receiver of

the air-pump indicates the pressure on the boiling liquid. Now Dufour found that after the water in A has been made to boil

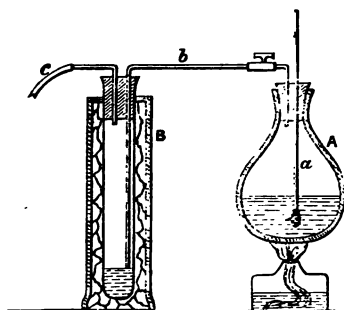


Fig. 65.

several times with the help of the air-pump and the lamp, and the air has been in this manner more and more removed, the water would not again boil at a given temperature at that pressure at which it would boil under ordinary circumstances, the temperature being the same, but that either the pressure had to be diminished or the water in A heated in order that ebulli-

tion should begin again. This will appear more clearly from the following table, in which the columns are headed by letters which have the following meaning :—

t is the temperature at which the water actually boiled.

p_1 ,, pressure under which the water should have boiled at the temperature t .

p ,, pressure actually observed when boiling commenced.

t_1 ,, temperature at which the water should have boiled under the pressure p .

In the last column, headed $t - t_1$, the number of degrees are given by which the boiling point was raised above the ordinary one.

t	p_1	p	t_1	$t - t_1$
°	Millimetres	Millimetres	°	°
92·2	569	505	89·0	3·2
65·5	189	99	51·7	13·8
53·8	111	46	36·8	17·0
52·7	105	33	30·8	21·9
71·6	250	108	53·5	18·1
70·1	234	79	46·9	23·2

It thus appears very distinctly that the temperature of the water constantly rises after each boiling, whereby more and more air is expelled.

In a second series of experiments Dufour prevented contact

of the boiling liquid with solid bodies by suspending drops in a liquid of the same specific gravity. A mixture of linseed-oil and oil of cloves, whose respective specific gravities are about '93 and 1'01, is so prepared that, for temperatures near 100° the density of the whole is nearly that of water. This mixture is placed in a cubical box of sheet-iron with two holes opposite each other, which are filled with glass so as to enable the observer to perceive what is passing within. The box is placed in a metallic envelope, which permits of its being heated laterally. When the temperature of 120° has been reached a large drop of water is allowed to fall into the mixture, which, on reaching the bottom of the box, is partially converted into vapour, and breaks up into a number of smaller drops, some of which take up a position between the two windows, so as to be visible to the observer. The temperature may now be raised to 140°, 150°, or even 180°, without producing evaporation of any of these drops. Since the maximum tension of steam at 180° is equal to ten atmospheres, we have here the striking phenomenon of a drop of water remaining liquid at this temperature, under no other pressure than that of the external air increased by an inch or two of oil.

In this case also the air necessary for evaporation is absent. If the drops be touched with a rod of metal, or better still, of wood, they are immediately converted into vapour with great violence, accompanied by a peculiar noise. This is explained by the fact that the rods used always carry a certain quantity of condensed air upon their surface, and by means of this air the evaporation is started. The truth of this explanation is proved by the fact, that when the rods have been used a certain number of times they lose their power of provoking ebullition, owing no doubt to the exhaustion of the air which was adhering to their surfaces.

If a retort is carefully washed with sulphuric acid, and then charged with water slightly acidulated, the air may be gradually more and more removed by repeated boiling. Let now the retort be connected with a pressure gauge and an air-pump, and the air exhausted until the liquid is under a pressure of only 150 millimetres. Under this pressure the water should ordinarily boil at a temperature of 60°. Dufour has shown that water thus treated will not boil even if the temperature is raised to 75°. If now, while the liquid is under these conditions of pressure and temperature, a current of electricity is sent through it by means of two platinum wires previously immersed in it, the bubbles of oxygen and hydrogen which are

evolved at the wires immediately produce violent ebullition, and a portion of the liquid is projected explosively.

Krebs, by careful removal of the air from water, has been enabled to raise the boiling point of water to nearly 200° ; and *Grove*, by similar experiments, has come to the conclusion that water, absolutely free from air, could not be made to boil at all.

The preceding experiments lead to the inference that a liquid, when not in contact with gas, has a difficulty in making a beginning of vaporisation, and may hence remain in the liquid state at much higher temperatures than those at which evaporation would begin if the necessary gas is supplied. According to Professor Carey Foster vapour may be substituted for air. He observed that when a liquid has been boiling for some time in a retort, it sometimes ceases to exhibit the movements characteristic of ebullition, although the amount of vapour evolved at the surface, as measured by the amount of liquid condensed in the receiver, continues undiminished. In this case it would appear that the superficial layer of liquid, which is in contact with its own vapour, is the only part that is free to vaporise.

These observations explain also the retardation of ebullition in glass vessels carefully washed, and the formation in these circumstances of large bubbles of steam, causing what is called a *bumping* during ebullition. This phenomenon is still more marked in the case of sulphuric acid. If this liquid is boiled in a glass vessel, enormous bubbles are formed at the sides, which, on account of the viscous nature of the liquid, raises the mass of liquid above them, and then lets it fall back with such violence as sometimes to break the vessel. This inconvenience may be overcome by throwing bits of platinum wire into the liquid, which carry with them a quantity of air, and thus facilitate evaporation.

Although there are thus great modifications of the temperature of a boiling liquid, depending on several circumstances, yet we may still maintain the law that the boiling point of a liquid under a definite pressure is definite and constant, provided that we consider as the temperature of the boiling liquid not that indicated by a thermometer inserted into the liquid itself, but that temperature which is given by a thermometer completely surrounded by the vapour produced by the boiling liquid. Rudberg had already enunciated this principle, on which the determination of the boiling point of thermometers is founded (see Art. 21, page 14). Marcet has more extensively confirmed the truth of the principle. In all his experiments,

alluded to above, he observed also the temperature of the steam, and found it in all cases $99^{\circ}9$, however much the fluctuations of the thermometer immersed in the liquid itself. Thus, as mean values of a great number of experiments he gives the following results for alcohol and water, the upper number in each column being the temperature of the liquid, and the lower number that of the vapour :—

In metal vessel		In glass vessel		In glass vessel containing iron filings	
Water	Alcohol	Water	Alcohol	Water	Alcohol
$100^{\circ}0$	$78^{\circ}50$	$101^{\circ}0$	$79^{\circ}20$	$100^{\circ}26$	$78^{\circ}75$
$99^{\circ}84$	$78^{\circ}35$	$99^{\circ}89$	$78^{\circ}40$	$99^{\circ}89$	$78^{\circ}33$

While thus the temperatures of the boiling liquids varied within appreciable quantities, those of the vapours remained constant, the trifling differences being entirely within the limits of errors of observation.

184. **Experiments on the retardation of ebullition.**—It has been shown that when a liquid, especially one free from air, be slowly heated, a retardation of ebullition may often be observed ; that is, the liquid boils at a temperature which is higher than its boiling point. In an open vessel this retardation is not easily produced, nor is the experiment in that case free from danger, because ebullition which has been retarded takes place always very suddenly and with great force, which is apt to shatter the vessel to pieces. The phenomenon may, however, be safely observed and conveniently produced by an instrument called the *water-hammer*, of which more is said farther on. In the mean time it will be sufficient to state that it consists of a glass tube with bulb, as shown in *fig. 67*, containing a quantity of water ; the air has been expelled above the water by boiling the latter and sealing the tube.

The apparatus is first held in a horizontal position, the bulb upwards, and the end of the tube is repeatedly and very moderately knocked against the side of the table, a door-post, or any other fixed piece of wood. At first the sound at each knock is sharp, because the water is thrown back by the elastic glass wall, while at the same time a few bubbles are produced. But very soon the sound becomes dull, and is like that produced by knocking an empty glass against the wood. The apparatus is

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now ready for the experiment. It is inclined until it assumes the position shown in *fig. 66*, taking special care that no bubble of vapour enters the tube ; for if this happens, the water in the tube sinks to the level of that in the bulb, as shown in *fig. 67*.

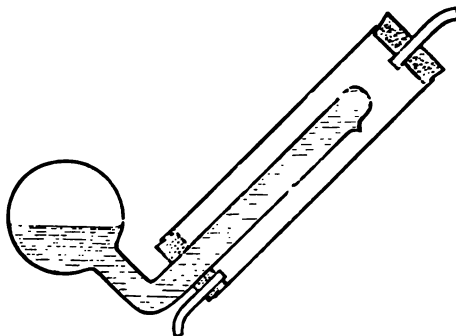


Fig. 66.

If the tube be warmed with both hands no vapour will be formed, and the tube may even be heated over the lamp for some time without formation of vapour. Not until the tube is strongly heated, does ebullition commence ; but when it takes place it causes a violent agitation of the liquid and the beginning of ebullition is distinctly felt by the hand.

Instead of using a flame for heating the tube it is preferable to heat it by steam. The tube is then fixed within a wider tube

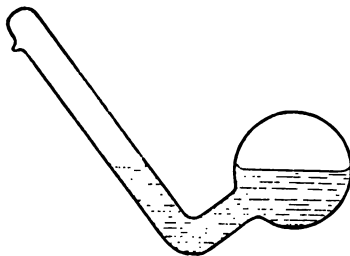


Fig. 67.

by means of a cork, as shown in *fig. 66*. Steam is passed through a small tube fixed in the cylinder by a perforated cork, and connected by india-rubber tubing with a flask containing water. The small tube below allows the steam to escape. The whole contrivance is fixed by the knee of the water-hammer in the

clump of a common retort-stand. The water in the flask is then made to boil, and ebullition in the water-hammer will not begin until the tube is considerably heated by the steam, while under ordinary circumstances the heat of the hand is sufficient to pro-

duce ebullition at the low pressure under which the water exists in the apparatus. The pressure of the vapour within the water-hammer is so small that the boiling point is very low, and in this case the retardation of ebullition takes place at a low temperature.

185. Ebullition at high pressures.—If a liquid is under an increasing pressure, its boiling point is retarded, and if the pressure is sufficiently raised the boiling of the liquid may be altogether prevented. Accordingly if water be boiled in a vessel, and the boiler be placed in communication with a reservoir containing air at the pressure of several atmospheres, the boiling point may be raised to 115° or more—a result often very useful for practical purposes. In a closed vessel the vapours produced finding no issue, their tension and their density increase with the temperature, but the rapid disengagement of vapour which constitutes ebullition is rendered impossible. Hence in a confined vessel water may be raised to a higher temperature than would be possible in the open air, but it will not boil. This is the case in an apparatus invented by *Papin*, a French physician, and called after him *Papin's Digester*. It consists of a cylindrical vessel of bronze or iron, possessing great strength, and covered with a lid secured by a powerful screw. In order to close the vessel hermetically, sheet lead is placed between the edges of the cover and the vessel. Since the tension of the steam increases rapidly with the temperature, it may finally acquire an enormous power. Thus at 200° the pressure is that of 16 atmospheres, or about 240 lbs. on the square inch. In order to obviate the risk of explosion, Papin introduced a device for preventing the pressure from exceeding a definite limit. His invention is nothing else but the well-known safety-valve, since applied to the boilers of steam-engines. It consists of a lever loaded with a known weight near one end and pressing near the opposite end, where its fulcrum is, upon a conical valve or stopper which closes an opening leading into the interior of the boiler. To understand its action we may suppose the area of the lower end of the stopper to be exactly one square inch, and that the pressure is not to exceed ten atmospheres, corresponding to a temperature of 180° . The magnitude and position of the weight may then be so arranged that the pressure on the hole is ten times 15 lbs. If the tension of the steam exceed ten atmospheres, the lever will be raised, the steam will escape, and the pressure will thus be relieved.

Papin's digester may be used for preparing food in localities, such as high mountains, where, in consequence of the diminished

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pressure, water boils at a temperature too low to soften animal fibre completely and extract the nutriment. It is, however, mostly used for extracting gelatine from bones. When bones are digested in this apparatus they are softened so that the gelatine which they contain is dissolved.

186. **Chemical relations of boiling points.**—The compounds of which organic chemistry takes cognizance are especially characterised by two properties, the small number of elements of which they consist—principally carbon, oxygen, hydrogen, and nitrogen—and further by the variety and complexity of the individual molecules which form the different compounds. Various observers, but especially *Kopp*, recognised relations between the constitutions of organic liquids and their boiling point. At first it was supposed that in general in a series of compounds to an equal *difference* of composition there corresponds also an equal difference in the temperature of the boiling point. This rule has not been confirmed in all cases; although, as seen from the following table where in a *homologous* series of compounds, of which each member differs in its composition from the preceding one by the addition of CH_2 (one atom of carbon and two of hydrogen) to the molecule of the latter, there appears a constant difference of the boiling point, that is, as we ascend from member to member, the boiling point rises by a definite number of degrees.

Members of Series	Chemical Formula	Boiling point	Elevation of boiling point
<i>Primary Alcohols.</i>			
Methyl	CH_3O	60°0	°
Ethyl	$\text{C}_2\text{H}_5\text{O}$	78°5	18°5
Propyl	$\text{C}_3\text{H}_7\text{O}$	97°5	19°0
Butyl	$\text{C}_4\text{H}_{10}\text{O}$	117°0	19°5
Amyl	$\text{C}_5\text{H}_{12}\text{O}$	137°0	20°0
Hexyl	$\text{C}_6\text{H}_{14}\text{O}$	157°0	20°0
<i>Derived Monobasic Acids.</i>			
Formic	CH_2O_2	99°0	
Acetic	$\text{C}_2\text{H}_4\text{O}_2$	119°0	20°0
Propionic	$\text{C}_3\text{H}_6\text{O}_2$	141°0	22°0
Butyric	$\text{C}_4\text{H}_8\text{O}_2$	162°0	21°0
Valerianic	$\text{C}_5\text{H}_{10}\text{O}_2$	184°0	22°0
Caproic	$\text{C}_6\text{H}_{12}\text{O}_2$	205°0	21°0
Oenanthic	$\text{C}_7\text{H}_{14}\text{O}_2$	224°0	19°0

187. **Latent heat of vapour.**—When a liquid is converted into vapour, a certain quantity of heat is absorbed and rendered latent in the vapour. The vapour which proceeds from the liquid has the same temperature as the liquid. It can be shown, however, experimentally, that, weight for weight, it contains much more heat. To render this manifest, let B (*fig. 68*)

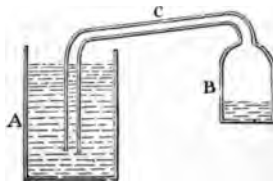


Fig. 68.

be a vessel containing water, which is kept in the state of ebullition and at the temperature of 100° by means of a lamp, or any other source of heat. Let the steam be conducted by a pipe c to a vessel A, which contains a quantity of water at the temperature of 0° . The steam issuing from the pipe is condensed by the cold water, and mixing with it gradually raises its temperature until it attains the temperature of 100° , after which the steam ceases to be condensed, and escapes in bubbles at the surface, as common air would if driven into the water from the pipe.

If the quantity of water in A be weighed before and after this process, its weight will be found to be increased in the ratio of about 11 to 13. Thus 11 lbs. of water at 0° , mixed with 2 lbs. of water in the form of steam at 100° , have produced 13 lbs. of water at 100° , so that the 2 lbs. of water which were introduced in the form of steam at 100° have been changed from the vaporous to the liquid state, retaining, however, their temperature of 100° , and have given to 11 lbs. of water which were previously in A at 0° as much heat as has been sufficient to raise that quantity to 100° .

It follows, therefore, that any given weight of water in the form of steam at 100° contains as much heat latent in it as is sufficient to raise $5\frac{1}{2}$ times its own weight of water from 0° to 100° , that is, through 100° of the thermometric scale.

If it be assumed that to raise a pound of water through 100° requires 100 times as much heat as to raise it one degree, it will follow that the quantity of latent heat contained in a pound of water in the form of steam at 100° is $5\frac{1}{2} \times 100 = 550$ times as much as would raise a pound of water through one degree.

This fact is usually expressed by stating that steam at 100° contains 550 thermal units of latent heat.

The same important fact can also be made manifest in the following manner. Let a lamp, or any source of heat which acts in a regular and uniform manner, be applied to a vessel containing any given quantity of water which is at 0° when the

process commences, and let the time be observed which the lamp takes to raise the water to 100° . Let the lamp continue to act in the same uniform manner until all the water has been converted into steam, and it will be found that the time necessary for such complete evaporation will be exactly $5\frac{1}{2}$ times that which was necessary to raise the water from the freezing to the boiling point. In a word, it will require $5\frac{1}{2}$ times as long an interval to convert any given quantity of water into steam as it will take to raise the same quantity of water, by the same source of heat, from the freezing to the boiling point; and consequently it follows that $5\frac{1}{2}$ times as much heat is absorbed in the evaporation of water as is necessary to raise it without evaporation through 100° of temperature.

Different experimental inquirers have estimated the heat rendered latent by water in the process of evaporation at 212° on Fahrenheit's scale, as follows:—

Watt	950	Despretz	955.8
Southern	945	Regnault	967.5
Lavoisier	1000	Favre and Silbermann	964.8
Rumford	1004.8		

In round numbers it may therefore be stated that as much heat is absorbed in converting a given quantity of water at 212° into steam as would be sufficient to raise the same quantity of water to the temperature of 1200° when not vaporised.

188. Latent heat at different pressures and temperatures.—It was observed at an early epoch in the progress of this inquiry, that the heat absorbed in vaporisation was less as the temperature of the vaporising liquid, and therefore the pressure of the generated vapour, was higher. Thus a given weight of water vaporised at 100° absorbs less heat than would the same quantity vaporised at 80° . It was generally assumed that the increase of latent heat, for lower as compared with higher temperatures, was equal to the difference of the sensible heats, and consequently that the latent heat added to the sensible heat, for the same liquid, must always produce the same sum. Thus, if water at 100° degrees requires for vaporisation 550 units of heat, water at 120° would only require 530 units, and water at 80° would require 570 units.

The simplicity of this result rendered it attractive; and, as the general result of experiments appeared to be in accordance with it, it was generally adopted. M. Regnault, however, afterwards submitted the question, not only of the latent heat of steam, but also the mutual relation of its pressure, temperature, and

density, to a rigorous experimental investigation, and has obtained results entitled to more confidence, and which show that the sum of the latent and sensible heats is not rigorously constant.

The pressures and densities obtained by M. Regnault are in accordance with those given in Table I., page 165. The latent heats are given in the following table, in Fahrenheit's degrees, where there is also given the sum of the sensible and latent heat, and shown, what does not seem to have been previously noticed, that they increase by an almost constant difference :—

Temperature	Latent Heat	Sum of Latent Heat and Sensible Heat	Temperature	Latent Heat	Sum of Latent Heat and Sensible Heat
32	1092·6	1124·6	248	939·6	1187·6
50	1080·0	1130·0	266	927·0	1193·0
68	1067·4	1135·4	284	914·4	1198·4
86	1054·8	1140·8	302	901·8	1203·8
104	1042·2	1146·2	320	889·2	1209·2
122	1029·6	1151·6	338	874·8	1212·8
140	1017·0	1157·0	356	862·2	1218·2
158	1004·4	1162·4	374	849·6	1223·6
176	991·8	1167·8	392	835·2	1227·2
194	979·2	1173·2	410	822·6	1232·6
212	966·6	1178·6	428	808·2	1236·2
230	952·2	1182·2	446	795·6	1241·6

It appears, therefore, that the sum of the latent and sensible heats is not constant, but increases by a constant difference—a difference however which, compared with the sum itself, is very small, and for limited ranges of the thermometric scale, when extreme accuracy is not required, may be disregarded.

189. **Experimental determination of latent heat of vapours.**—It would clearly be possible, since the apparatus sketched in *fig. 68* is essentially nothing else but a distilling apparatus, B being the boiler and A the condensing vessel (see farther on, Art. 194, page 229), to use such an apparatus for the determination of the latent heat of vapours, provided that care is taken to ascertain always accurately how much vapour has been condensed in a given time, and how much heat it has yielded to the cold water in the condenser. Hence a distilling apparatus need only be provided with a calorimeter suitable for these two determinations, and it will serve for an experimental research into latent heat. *Black* was the first to take advantage of this

principle; and all succeeding experiments have, with various modifications, maintained the principle of the method. The differences which are observed in the results obtained by different physicists are chiefly due to sources of errors which have been overlooked or not sufficiently guarded against by one or the other experimenter engaged in the enquiry. *Brix* boiled the liquid in a small retort from which the disengaged vapour entered a cylindrical ring-shaped hollow vessel, which served as condenser. This vessel was contained in a cylindrical vessel of sheet-brass, forming the calorimeter. An open tube passed from the condenser through the calorimeter, so as to connect the condenser with the air and prevent a rise of pressure in the retort. A thermometer dipped into the water in the calorimeter, the quantity of which was carefully weighed. Care was also taken to prevent heat being radiated, and conducted to, or from the apparatus. The experiments of *Despretz* were quite similar to those of *Brix*, but the latter added an arrangement for stirring the water in the calorimeter, and thus obtaining a more correct indication of the temperature of the water. The following are the results obtained by *Brix* and *Despretz*:

Liquids	Latent heat of vapours	
Water	550	540
Alcohol	210	206.6
Common ether	89.96	90.7
Turpentine	74.04	76.75
Oil of lemons	79.81	
	<u>Brix</u>	<u>Despretz</u>

These results are thus nearly the same. *Regnault* used the same method for various liquids with the following results:

	Latent heat.
Amylic alcohol	204.03
Turpentine	134.85
Oil of lemons	156.00
Naphtha	189.81
Ethyl chloride	95.02
Ethyl iodide	57.30
Bromine	49.77
Chloride of tin	54.14
Chloride of arsenic	67.73
Chloride of phosphorus	65.24
Acetic ether	145.69

These investigations have all been made with vapours under the ordinary pressure of the atmosphere. Watt, Southern, and Regnault devoted themselves to the question, how much heat is required for the production of equal amounts of vapour under pressures differing from the ordinary atmospheric pressure.

190. Watt's and Southern's laws. Regnault's results.—

Watt boiled water at a pressure which was about equal to one-third of the ordinary atmospheric pressure, and condensed the vapour in a calorimeter. At a temperature of 63° he found the latent heat of the generated vapour 559, that is, it required 559 thermal units to convert a kilogramme of water at 63° into saturated vapour at 63° ; hence, in accordance with this experiment, it requires $559 + 63 = 622$ thermal units to convert a kilogramme of water at 0° into steam saturated at 63° C. Now in former experiments Watt found the latent heat of saturated steam at 100° to be 524; that is, it required $524 + 100 = 624$ thermal units to convert a kilogramme of water at 0° into steam saturated at 100° . The two quantities of heat required to convert a given quantity of water at 0° into steam saturated at different temperatures were thus sensibly equal, and hence Watt concluded that the quantity of heat requisite for converting a kilogramme of water into saturated steam is always the same at whatever temperature the steam may be saturated. This law of Watt is often enunciated thus: The whole quantity of heat necessary to raise a given weight of water from zero to any temperature, and to evaporate it entirely at that temperature, is a constant quantity. According to this law the latent heat of steam decreases constantly as the temperature increases, and if we suppose the specific heat of water to be constant at all temperatures, the latent heat decreases exactly by one thermal unit for every increase of one degree of temperature. Thus at 0° the latent heat of steam saturated at 0° is 622, at 50° it is 572, and at 100° 522 thermal units.

Southern, who made a more extensive series of experiments, was led to a different conclusion. He enunciated the fact that the latent heat of saturated steam is at all temperatures the same and equal to 523 units, this constant being the same which Watt had found for steam at 100° . Southern and Creighton determined the latent heat of steam, after the method previously described, at pressures which were much higher than the ordinary pressure of the atmosphere, and found it to be—

523.3 at a vapour-tension of 1,016 millimetres.

523.3	„	„	„	2,032	„
527.7	„	„	„	3,048	„

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According to Southern's law the latent heat at 0° , required to evaporate a kilogramme of water at 0° is 523 ; at 100° it is 623, at 200° it is 723 thermal units, and so on. In other words the sum of the sensible and latent heat at any temperature increases by one unit for every rise of temperature of one degree.

It was reserved for Regnault to prove by most carefully arranged experiments that both these laws of Watt and Southern were inaccurate, that neither the *total heat* (sum of sensible and latent heat) of saturated steam was constant, nor that the latent heat of evaporation was the same at all temperatures. In the following tables a number of Regnault's results are given, which show that the latent heat decreases with the temperature, but not so rapidly as Watt's law assumes, and that the total heat increases, but not so rapidly as Southern's law indicates.

Tension of vapour	Temperature of vapour	Total heat	Latent heat
Millimetres	$^{\circ}$		
170.91	63.02	625.5	562.5
369.80	81.03	628.8	547.8
760.00	100.00	636.67	536.67
1448.17	119.25	642.3	523.0
2285.26	134.4	649.0	514.6
3042.51	144.3	649.7	505.4
3883.14	153.5	650.1	496.6
4643.15	160.3	653.1	492.8
6127.67	171.6	655.5	483.9
8056.49	183.2	662.4	479.2
10354.84	194.8	666.0	471.2

From his results Regnault was not enabled to enunciate a simple law, according to which the quantity of heat required at different temperatures for the production of saturated steam is regulated. He represented therefore the dependence of the quantity of heat from the temperature by the empirical formulæ—

$$Q = A + Bt + ct^2 \dots$$

in which Q is total quantity of heat required for evaporation, and A , B , C , are constants to be determined by experiments. Regnault found from his experiments at 100° and at 195° that

$$A = 606.5$$

$$B = 0.305$$

$$C = 0.0$$

Hence at these temperatures

$$q = 606.5 + 0.305t.$$

This equation gives not only the quantities required between 100° and 195° , but also those at lower temperatures, with great correctness. It follows that the total quantity of heat in steam at any temperature is equal to the quantity of heat in a kilogramme of steam at 0° , increased by the product $0.305t$.

In order to find the latent heat of steam at any temperature t , we must first deduct from the total heat q the quantity (q) required for heating a kilogramme of water to the temperature t , which is given in Art. 105, page 113, as

$$q = t + 0.00002t^2 + 0.0000003t^3.$$

Hence :

$$\begin{aligned}\text{Latent heat} &= q - q \\ &= 606.5 - 0.695t - 0.00002t^2 - 0.0000003t^3.\end{aligned}$$

Thus we find the following values at various temperatures :

$t =$	0°	40°	80°	100°	120°	160°	200°
Latent heat =	606.5	578.7	550.6	536.5	522.3	493.6	464.3.

These results agree exceedingly well with those calculated from an approximate formula, which has been given by *Clausius* from theoretical considerations, viz.—

$$\text{Latent heat} = 607 - 0.708t,$$

which gives for the corresponding values above

at 0°	40°	80°	100°	120°	160°	200°
607	578.6	550.36	536.2	522.04	493.72	465.4.

191. **Latent heat of other vapours.**—Regnault made also careful experiments on the vapours of other liquids, varying the pressure during the experiments between about 100 and 8,000 millimetres. He found that in most of the liquids which were subjected to experiment, the total quantities of heat required for evaporation at any temperature could be represented by a formula of the form given in the preceding article with reference to water, viz. :—

$$Q = A + Bt + Ct^2,$$

and that hence the latent heat of their vapours at any temperature could be represented by equations similar to the above, deducting in each case the quantity of heat required to heat each liquid to the temperature under consideration. The constants, A , B , C , for the total heat are the following for the various liquids named :—

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	A	B	C
Carbon disulphide . . .	90°0	0°14601	-0°0004123
Ether	94°0	0°4500	-0°0005555
Benzine	109°0	0°2443	-0°0001315
Chloroform	67°0	0°1375	0°0
Chloride of carbon . . .	52°0	0°1463	-0°000172
Acetone	104°5	0°3664	-0°000516

The latent heat of these substances, calculated with due regard to their various specific heats, as given in the tables on pages 113 and 120, are hence the following :—

Carbon disulphide . . .	90°0-0°08922t-0°0004938t ²
Ether	94°0-0°07901t-0°0008514t ²
Benzine	109°0-0°13550t-0°0005885t ²
Chloroform	67°0-0°09485t-0°0000507t ²
Chloride of carbon . . .	52°0-0°05173t-0°0002626t ²
Acetone	140°5-0°13999t-0°0009125t ²

The latent heat of the vapours of other liquids has also been ascertained by MM. Favre and Silbermann, and is given, as well as the specific heat, in the following table :—

Names of Substances	Temperature	Specific Heat	Latent Heat
Water	212° F.	1	964°8
Carburetted hydrogen	392	0°49	108
Ditto	482	0°50	108
Pyroligneous acid	151°7	0°67	475°2
Alcohol, absolute	172°4	0°64	374°4
„ Valerianic	172°4	0°59	217°8
„ ethalic	172°4	0°51	104°4
Ether, sulphuric	100°4	0°50	163°8
„ Valerianic	236°3	0°52	124°2
Acid, formic	212	0°65	304°2
„ acetic	248	0°51	183°6
„ butyric	327°2	0°41	207
„ Valerianic	347	0°48	187°2
Ether, acetic	165°2	0°48	190°8
Butyrate of methylene	199°4	0°49	156°6
Essence of turpentine	312°8	0°47	124°2
Terebene	312°8	0°52	120°6
Oil of lemons	329	0°50	126

192. **Latent heat of Alcohol.**—While for all vapours mentioned in the preceding article the total heat constantly increases, and the latent heat decreases, the latent heat of evaporation of alcohol exhibits such remarkable inequalities, that neither for the total heat nor for the latent heat a formula could be constructed similar to those given for other vapours. Regnault confined himself to the construction of a curve representing this anomalous behaviour. The following table gives the values thus obtained by graphical delineation, from 10 to 10 degrees :—

Temperature	Total Heat	Latent heat
0	236.5	236.5
10	244.4	238.8
20	252.0	240.6
30	258.0	240.5
40	262.0	238.3
50	264.0	233.8
60	265.0	227.6
70	265.2	220.6
80	265.2	213.1
90	266.0	206.0
100	267.3	199.1
110	269.6	192.9
120	272.5	186.8
130	276.0	181.0
140	280.5	175.8
150	285.3	170.5

It will thus be seen that the latent heat increases up to a temperature of about 30°, and then decreases, at first slowly, then more rapidly, and then again more slowly. Regnault thinks it possible that alcohol, when boiling under high pressure may generate vapour which undergoes some molecular change while in that state, resuming its ordinary molecular condition when the pressure is released. On the other hand he admits that it is exceedingly difficult to obtain the liquid in a really pure state, and that it showed similar anomalies in all experiments to which it was subjected.

193. **Condensation of vapour.**—Since by continually imparting heat to any body in the liquid state, it at length passes into the form of vapour, analogy suggests that by continually

withdrawing heat from a body in the vaporous state, it must necessarily return to the liquid state; and this is accordingly generally true. The vapour, being exposed to cold, is deprived of a part of that heat which is necessary to sustain it in the aeriform state, and a part of it is accordingly restored to the liquid form; and this continues until, by the continual abstraction of heat, the whole of the vapour becomes liquid: and as a liquid in passing to the vaporous form undergoes an immense expansion or increase of bulk, so a vapour in returning to the liquid form undergoes a corresponding and equal diminution of bulk. A cubic inch of water, transformed into steam at 100° , enlarges in magnitude to nearly 1700 cubic inches. The same steam being reconverted into water, by abstracting from it the heat communicated in its vaporisation, will be restored to its former bulk, and will form one cubic inch of water at 100° . Vapours arising from other liquids will undergo a like change, differing only in the degree of diminution of volume which they suffer respectively. The diminished space into which vapour is contracted when it passes into the liquid form, has caused this process to be called *condensation*.

The absorption of heat in the process by which liquids are converted into vapour will explain why a vessel containing a liquid that is constantly exposed to the action of fire can never receive such an amount of heat as would injure it. A tin kettle containing water may be exposed to the action of the most fierce furnace, and remain uninjured; but if it be exposed, without containing water, to the most moderate fire, it will soon be attacked. The heat which the fire imparts to the kettle containing water is immediately absorbed by the steam into which the water is converted. So long as water is contained in the vessel, this absorption of heat will continue; but if any part of the vessel not containing water be exposed to the fire, the metal will probably, if sufficient heat is applied, be fused, and the vessel destroyed.

194. **Distillation.**—This process depends upon the successive evaporation and condensation of liquids, and is used for the purpose of separating liquids from substances which they may hold in solution.

The process by which water is first converted into vapour and then restored to the state of water is called distillation, from a Latin word *DISTILLATIO*, which signifies ‘falling in drops.’ The conversion of the vapour into liquid in the condenser usually proceeds so slowly that the liquid falls from the spout

of the condenser, not in a continuous stream, but in a succession of drops.

In the industrial arts, and in chemical laboratories, where water absolutely pure is needed in considerable quantities, its distillation is conducted in an apparatus which is represented in *fig. 69*.

This distilling apparatus, or alembic, consists of a copper boiler, *A*, fixed in a brick furnace, having a dome-shaped cover. *B*, adapted to it, from which a bent tube, *b c d*, proceeds, and is connected with a spiral tube called a *worm*. This worm is enclosed in a large cylindrical cistern, *p q j r*, constructed in metal, and which is kept constantly filled with cold water. The lowest part of the worm passes out of this cistern near its bottom, and terminates at *a*, over the mouth of a jar, *c*, intended to receive the distilled water. An opening, *t*, having a steam-tight stopper,

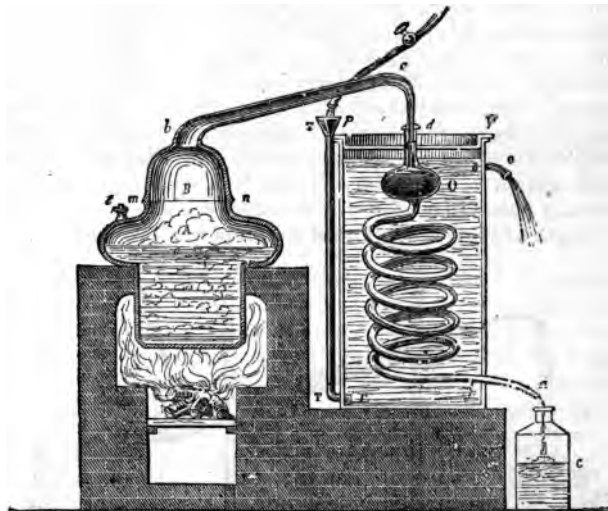


Fig. 69.

is provided in the boiler, through which the water to be distilled is introduced into it.

The vapour issuing from the boiler through the tube, *b c d*, passes into the worm, being first received by the vessel, *o*, where the condensation begins.

Passing next through the coils of the worm, it is exposed to

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the contact of its cold surface, and is entirely condensed and reduced to the liquid state before it arrives at the lower extremity, *a*, from which it trickles in drops into the jar, *c*.

The heat disengaged from the vapour in the process of condensation being constantly imparted to the water in the cistern *p q j r*, that water would be gradually warmed, and if it were not discharged and replaced by cold water, it would no longer keep the worm cold enough to condense the vapour. A supply of cold water is therefore introduced through a pipe, *r t*, while the heated water flows away through the pipe of discharge, *o*.

Heated water, being lighter bulk for bulk than cold water, will float upon the latter without mixing with it, unless the liquid be agitated. The cold water, therefore, being introduced at the lowest part, *r*, of the cistern, will form the inferior strata, while the heated water will collect at the superior strata, and, being pressed upwards by the cold water, will flow out at *o*. The supply pipe, *p*, which feeds the pipe *r t*, and the discharge pipe, *o*, may be, and generally are, so regulated that the water discharged from *o* is very little below the temperature of the vapour coming from the boiler, while the water of the lowest strata is as cold as the external atmosphere. The vapour, therefore, which enters at *d*, is at first only partially condensed, the condensation being rapidly increased as, winding through the worm, it passes in contact with a surface colder and colder until, at length arriving at the lowest coil, it is wholly condensed.

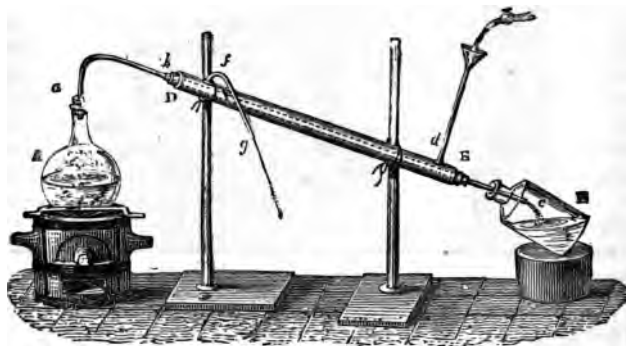


Fig. 70.

The heated water which flows from the discharge pipe, *o*, may be used to feed the boiler, *b*; and being already at a high temperature, an economy of fuel is thus effected.

When extreme purity is required in the distilled water, it is evaporated at a temperature lower than 100° , because at that temperature a certain small portion of the foreign matters which it holds in solution sometimes goes over in the vaporous state through the worm, and is ultimately deposited in the jar, *c*. The lower the temperature at which the water in the boiler is evaporated, the less of this impurity will pass through the worm.

By these expedients, with proper precautions, water absolutely pure, and entirely free from all foreign matter, may be obtained.

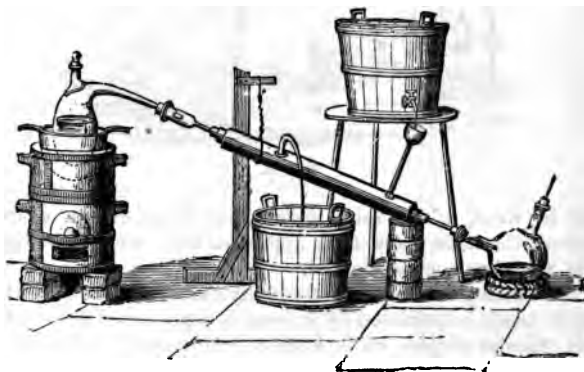


Fig. 71.

195. **Apparatus to distil volatile liquids.**— In physical and chemical researches it is frequently necessary to distil very volatile liquids, the vapour of which would be wasted or lost if it were not condensed. In such cases apparatus for distillation such as those represented in *figs.* 70 and 71, are generally used in the laboratories. In *fig.* 70, the globular glass flask *A*, placed upon a charcoal furnace, contains the liquid to be distilled; it is connected by a bent tube *a b c* with a condensing vessel *B*. The tube *a b c* is surrounded by a larger tube, *D E*, which is made water-tight at the ends; this tube, which is usually made of tin, is kept filled with cold water by a lateral tube *d*, and the water is discharged from it by another lateral tube *f g*. The vapour, in passing through the tube *a b c*, is condensed by the cold to which it is exposed between *D* and *E*.

In *fig.* 71 another variety of the same apparatus is shown, which is used when the vessels from which the liquids are distilled are liable to be broken by the unequal action of the heat when in immediate contact with the charcoal. In the apparatus

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shown in *fig. 71*, the flask *A* is replaced by a tubulated retort which is immersed in a sand bath heated by the charcoal. Another tubulated retort replaces the vessel *B*.

When the quantity of liquid to be distilled is not considerable, a more simple apparatus, such as that represented in *fig. 72*,

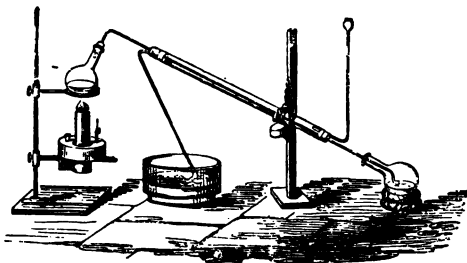


Fig. 72.

may be used, where an Argand lamp replaces the charcoal furnace, the other parts of the apparatus being easily intelligible after what has been explained.

A still more convenient and equally simple contrivance, which may be easily constructed by anyone, is represented in *fig. 73*. A wide cylinder of glass, *cc*, is closed at both ends by corks. A tube *ab*, having a somewhat narrower opening below than that above, passes through both corks of the wider tube; its upper end *a* is closed air-tight by a cork perforated for a narrow tube which leads to a vessel in which the steam is generated. The lower end is loosely placed into the neck of a vessel which serves for receiving the condensed liquid. Cold water passes into *cc* by means of the narrow tube *d*, which reaches nearly to the bottom of *cc*, while the heated water flows off at the top of *cc* through the narrow tube *e* which is fixed in the side of it.

The upper cork serves only for keeping the tubes *cc* and *d* in a steady position, and need not fit very tight; but the lower cork must close the lower aperture perfectly water-tight, or otherwise the impure water in the condenser *cc* will run between cork and sides into the receiver, mix with the distilled liquid in it, and render it impure again. The tube *d* may be attached by a piece of india-rubber tubing to one end of a syphon which is set up at a suitable height above the apparatus for distilling; or it may be connected with the water-pipe, and the flow may be regulated by means of the water-tap.

That solid bodies remain behind in the distillation of a

liquid may be shown experimentally by adding to the water to be distilled a little salt and a trace of magenta colour. The distilled water has no taste and is colourless, the magenta being generally deposited upon the sides of the boiling flask.

196. **Crystallisation produced by distillation.**—The process of distillation supplies an easy and convenient means of obtaining bodies in a crystallised state. It is found that, when solid bodies are dissolved in water, there is a certain limit to the quantity which can be held in solution, and that, if a greater quantity be thrown into the water, it will sink to the bottom without being dissolved. This is a fact which anyone can ascertain by dissolving common salt in water. When so much of the solid is supplied as the water is capable of dissolving, the solution is said to be *saturated*, and the particular proportion of the quantity dissolved to the entire quantity of water is called the point of saturation.

Now it is found that, in general, the point of saturation varies with the temperature of the water; the higher that temperature is, the higher will in general the point of saturation be, or, what is the same, the greater will be the quantity of the solid which a given quantity of water can hold in solution. If, therefore, water at the boiling point be saturated, it must deposit, according as it cools, a certain quantity of the substance it holds in solution; and it is found, in general, that the substance thus deposited will be in a state of crystallisation. But crystallisation may also be produced by evaporation, independently of any change of temperature. Thus, for example, if water at the boiling point be saturated with salt, the quantity of water being diminished by that which escapes in the form of steam, the remainder being incapable of holding the same quantity of salt in solution, a part of the salt

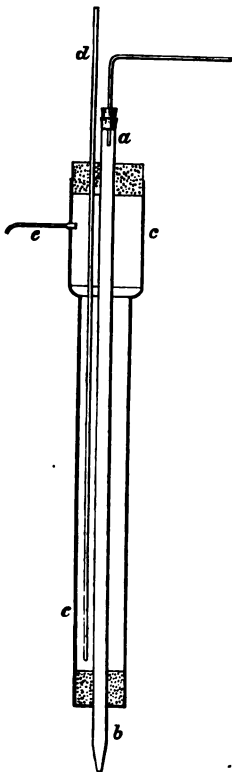


Fig. 73.

will be deposited in the solid form, and the part thus deposited will increase as the water is evaporated. The beauty of the crystalline forms will, in this case, however, be interfered with by the agitation of the liquid.

This effect produces very injurious consequences in the boilers of steam vessels. Such boilers being supplied with sea water, holding salts of different sorts in solution, the continued evaporation at length raises the water in the boiler to the point of saturation, after which salt will be deposited, which, accumulating in the boiler, will intercept more or less of the heat, and thus produce waste of fuel and other injurious consequences.

Very similar is the action of hard water on the boilers of ordinary steam engines. Those waters which contain compounds of calcium or magnesium are generally spoken of as *hard*, in opposition to those waters which do not contain these compounds, and are called *soft*. Many hard waters become softer by boiling, the carbonic acid which they contain being expelled by this means, and the carbonate of lime, and part of the sulphate of lime which the carbonic acid enabled them to hold in solution, are then deposited, and cause a 'fur' or incrustation upon the inside of the boiler.

197. **Decomposition by evaporation.**—In physical researches it is often required to obtain in a separate state the substances which water holds in solution. For this purpose the solution is poured into a porcelain cup, which is placed over a spirit lamp, as shown in *fig. 74*; and the water being thus evaporated, the substance held in solution remains in the cup. In chemical analyses, however, where it is necessary to obtain a



Fig. 74.

rigorous estimate of the quantity held in solution, this process requires to be conducted with many precautions. Thus, the liquid must not be raised to the boiling point, because in that case the steam bubbles produced at the bottom of the cup would

rise with such force as to scatter, in the form of spray, more or less of the substance which it is necessary to preserve. Sometimes the cup containing the solution to be evaporated is placed in another containing water, by which means the heat imparted to the former is moderated and regulated. In other cases the water is omitted, and the cup containing the solution is suspended in a cup of copper, which is empty, or which, more properly speaking, is filled with air. In other cases, again, the cup containing the solution to be evaporated is placed in a sand bath raised to a moderate temperature by a wood fire.

198. **Some effects of steam. The water-hammer.**—The peculiar hissing sound which is heard when steam is condensed by being passed into water is caused by the clashing together of particles of water which are urged by atmospheric pressure to rush in from all sides to occupy the space left vacuous by the condensed steam. As water is very little compressible the sound is very similar to that produced by striking solid bodies together.

When steam is generated in a vessel only partly filled with water it will after a time sweep out the air from the space above the water, and if the steam is now condensed an almost perfect vacuum may be produced. If water is boiled for some time in a flask closed by a perforated cork through which a glass tube is passed connected at the end with a short piece of india-rubber tubing, the latter may be closed by a clamp and the flame removed. Under these circumstances the space within the retort above the liquid contains no longer any air, but is filled with steam, of which the pressure is at first the same as that of the atmosphere, but as the temperature decreases the pressure also becomes less, and finally there will be in the retort only very rarefied steam exerting an inconsiderable pressure.

In the same manner the previously mentioned water-hammer (*fig. 75, A and B*) is exhausted of air. Where the small point

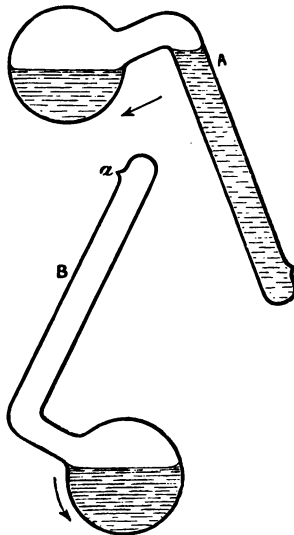


Fig. 75.

appears at *a*, there was a short narrow tube through the opening of which the air has been driven out, and which was then closed with the blowpipe. When the apparatus is inverted so that some of the water strikes against the extremity of the tube, or against another portion of the liquid contained in it, a sharp sound is produced similar to that which accompanies the condensation of steam in water. It resembles so much the shock of two solid bodies that on hearing the sound for the first time, it appears as if the glass had been cracked. The sound is particularly sharp if the apparatus is either held in the position *A*, *fig. 75*, and moved quickly in the direction of the arrow, so that the water in the bulb strikes against that in the tube, or in position *B*, and turned rapidly in the direction of the arrow so that the whole water falls from the bulb into the empty tube and strikes against the glass.

199. **Reaction of steam. The Eolipyle.**—It has already been shown in the treatise on **HYDROSTATICS**, in this series, page 303, Art. 230, that if water be discharged from a vessel by a small orifice or a tube, and the vessel is moveable on an axis, the discharge of the water will produce a reaction in an opposite direction to that of efflux, and the vessel will rotate. An arrangement of this kind is usually called Barker's mill. Now when a vessel containing water is heated, and there is only a small orifice in the vessel, then the escape of steam is impeded,



Fig. 76.

and the temperature of the water rises to above 100° . The tension of the steam is in that case higher than the atmospheric pressure, and the steam is ejected through the orifice with considerable force. Such a jet of steam is especially well adapted for showing the phenomenon of reaction. A reaction apparatus moved by steam may be had from the dealers under

the name of *Hero's engine*, or *Eolipyle*. It consists of a hollow spherical vessel, capable of rotating about an axis and fitted with two tubular appendages bent at right angles and having narrow apertures, as seen in *fig. 76*. By immersing one of the apertures in water and sucking at the other, the vessel may be partly

filled with water, which is then made to boil by the application of a lamp. Very soon two jets of vapour are forcibly discharged through the apertures and on the principal of reaction the globular vessel is driven round in an opposite direction.

200. Freezing by evaporation.—The evaporation of liquids is retarded by the pressure of the air surrounding them, and is consequently promoted when that pressure is diminished or removed. A method of producing artificial ice is founded upon this principle.

A cup of unglazed porcelain, containing water, is placed upon a large glass dish containing sulphuric acid. The dish and cup are then placed upon the plate of an air-pump (*fig. 77*), and being covered by a receiver, the air is exhausted.

The water, being relieved from the atmospheric pressure, freely evaporates, and the receiver would soon be filled with an atmosphere of its vapour, the pressure of which would arrest the evaporation; but the sulphuric acid, as explained in Art. 182, page 209, absorbs the vapour as fast as it is produced, and the water being thus free from pressure, the evaporation continues.

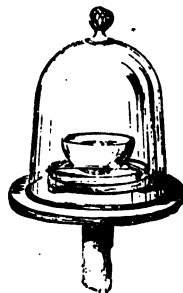


Fig. 77.

But in the change from the liquid to the vaporous state a large quantity of heat is absorbed and rendered latent, as already explained, and all this heat must be taken from the water which remains unevaporated. Thus, for every drop of water which is converted into vapour, the water which remains in the cup will be deprived of as much heat as would be sufficient to raise the temperature of a similar drop about 550 degrees higher if it were not evaporated. This great loss of heat causes the water which remains unevaporated in the cup to fall in temperature and soon to congeal.

On the absorption of heat by evaporation is also founded the very instructive instrument called *Wollaston's cryophorus* (cold-bearer). As shown in *fig. 78*, it consists of two glass bulbs, A and B, connected by a tube. Water was put in the bulb A, and whilst a small orifice was left open at the bottom of the bulb B, the water was boiled. As in the case of the water-hammer, the steam escaping from the water chased out the air, and when this was all expelled the orifice was closed by means of a blow-pipe. When the water has cooled down to the ordinary temperature, there is only water and vapour of water, exerting a very slight pressure, left in the apparatus. If now the bulb A

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be placed in a vessel, so as to exclude currents of air which would affect and possibly delay the result, while the other bulb is plunged in a freezing mixture, the vapour present and that



Fig. 78.

which escapes from the water is condensed, and after some time the water in A begins to freeze.

201. **Applications of latent heat of steam.**—The latent heat of steam may be used with convenience for many domestic purposes. In cookery, if the steam raised from boiling water be allowed to pass through meat or vegetables, it will be condensed upon their surface, imparting to them the latent heat which it contained before its condensation, and thus they will be as effectually boiled as if they were immersed in boiling water.

In dwelling-houses, where pipes convey cold water to different parts of the building, steam-pipes carried through the building will enable hot water to be procured in every part of it with speed and facility. The cock of the steam-pipe being immersed in a vessel containing cold water, the steam which escapes from it will be condensed by the water, which, receiving the latent heat, will soon be raised to any required temperature below the boiling point. Warm baths may thus be prepared in a few minutes, the water of which would require a long period to boil.

The variations of temperature incident to any part of the globe are included within narrow limits, and these limits determine the bodies which are found to exist there most commonly in the solid, liquid, or gaseous state.

A body whose boiling point is below the lowest temperature of the climate must always exist in the state of vapour or gas; and one whose point of fusion is above the highest temperature must always be solid. Bodies whose point of fusion is below the lowest temperature, while their boiling point is above the highest temperature, will be permanent liquids. A body whose point of fusion is a little above the lowest limit of the tempera-

ture, will exist generally as a liquid, but occasionally as a solid. Water in these climates is an example of this. A liquid, on the other hand, whose boiling point is a little below the highest limit of temperature, will generally exist in the liquid, but occasionally in the gaseous form. Ether in hot climates is an example of this, its boiling point being 98° on Fahrenheit's scale, a temperature not unfrequently observed in hot countries. ●

Some bodies, at our ordinary temperature, are only permanently retained in the liquid state by the atmospheric pressure. Ether and alcohol are examples of these. If these liquids be placed under the receiver of an air pump, and the pressure of the air be only partially removed, they will boil at the common temperature of the air.

CHAPTER IX.

HYGROMETRY.

202. **Object of Hygrometry.**—The object of hygrometry is to observe the amount of moisture contained in the atmosphere. The instruments used for this purpose are called hygrometers.

The gaseous envelope which surrounds the earth may be considered as composed of two distinct atmospheres—an atmosphere of dry air and an atmosphere of vapour. The dry air is always a gas, and its quantity constant from year to year; but the vapour of water does not always remain in the gaseous state, and the quantity present in the atmosphere is, by the processes of evaporation and condensation, varying every instant. That the air is never completely dry, may be easily proved by a simple experiment. There are substances, like chloride of calcium, sulphuric acid, &c., which possess a great chemical affinity for water, and are hence called *hygrometric* substances. If one of these substances be at any time exposed to the air, they are found to absorb aqueous vapour. On the other hand the air in general is not completely saturated, hence besides ascertaining the actual amount of vapour present, it is more often the real object of an experiment in hygrometry to ascertain the ratio of the amount present at any time to the amount which would completely saturate the air at the temperature which prevails at the time of the experiment in that locality. This ratio has received the name *humidity*, or rather *relative*

humidity, and it is said to indicate the 'hygrometric state' of the atmosphere.

To ascertain with exactness the hygrometric condition of the air is of the utmost importance, both to the physician and agriculturist, as well as to the scientific inquirer. By observing the varying amount of vapour or moisture in the air the physician is enabled to regulate its condition as best suited to his patient's requirements; while the agriculturist, by closely watching the movements of the barometer in connection with the hygrometer, can anticipate probable atmospheric changes that may prove beneficial or injurious to his crops.

203. **Relative and absolute humidity.**—As upon the relative humidity, as defined in the preceding article, our sensations of the dryness and moisture of the air chiefly depend, so do the words 'humid,' or moist, and 'dry,' as applied to air in ordinary language, nearly correspond to the technical use of the word relative humidity, and air is usually said to be dry when its humidity is considerably below the average. Thus the air in a room heated by a hot stove contains as much vapour weight for weight as the open air outside; but it is drier, because being warmer it could at this higher temperature contain considerably more vapour than it actually contains. In like manner the air is drier at noon than at midnight, though the amount of vapour present is about the same; and it is for the most part drier in summer than in winter, though the amount of vapour present is much greater in summer. Relative humidity differs completely from absolute humidity, which implies nothing more than the absolute amount of vapour in a given quantity of air. Thus suppose the temperature of the air to be 40° F. and quite saturated with vapour, and then to be suddenly raised to 50°, without any addition being made to its vapour, its absolute humidity would in each case be the same, but its relative humidity has considerably changed. In popular language it would be considered very damp air in the former case and very dry air in the latter.

The relative humidity is usually expressed as a percentage. When the humidity is 100, the air is completely saturated; but if the vapour actually present is seven-tenths of that required for complete saturation, the humidity is seven-tenths of 100, or is said to be 70. We may thus define relative humidity as: *the weight of aqueous vapour in a given volume of air, expressed as a percentage of the weight of vapour which at the same temperature would occupy the same volume at saturation.* From the laws of Boyle and Mariotte it follows, that at the same temperature, the volume remaining the same, the weight of vapour in a non-

saturated space increases with the pressure, and therefore with the tension of vapour itself. Hence, instead of using the ratio of the weights of the vapour present and required for saturation, we may use the corresponding tensions, and define humidity, or the hygrometric state, as *the ratio of the tension of the aqueous vapour which the air actually contains to the tension of the vapour which it would contain at the same temperature if it were saturated.*

204. **The dew-point.**—Let us suppose that air which contains at some definite temperature a quantity of vapour, not sufficient for saturation at that temperature, is gradually cooled while the pressure remains the same through the experiment. The density of the air as well as that of the vapour will under these circumstances increase, because vapour removed from its liquid behaves nearly like dry air, and a point must be reached at which the density of the vapour becomes equal to the maximum density corresponding to the temperature, to which the air and vapour have been lowered. This temperature is called the *dew-point* of the given mass. If the temperature be further lowered, condensation of a portion of vapour must clearly take place, and if some object be present upon which the condensed portion may be deposited, the surface will exhibit a layer of dew or moisture. It follows that the relative humidity of the air can be exactly determined by ascertaining experimentally its dew-point. For, let t be the actual temperature of the air, as given by an ordinary thermometer. To this temperature corresponds a maximum tension of vapour, which we may call p , and which is experimentally determined once for all and given in Table I. page 167. Further let t be the observed temperature of the dew-point, and p the corresponding maximum tension of vapour, then we shall have

$$\text{Relative humidity} = \frac{P}{p}.$$

On this principle several hygrometers have been constructed.

The following are the most important forms of instruments chiefly in use :—

205. **Daniell's Hygrometer.**—This was the first accurate instrument invented for the purpose, and may still be used to determine the dew-point with considerable ease and exactness. It is represented in *fig. 79*, and consists of a small glass syphon, at each end of which is a thin glass bulb about $1\frac{1}{4}$ inch in diameter. The longer leg, *a b*, is about 4 inches long, and contains a small but very delicate thermometer, the bulb of which is within the terminal glass ball. The syphon contains so

much common ether as when poured into the lower bulb *c* will rather more than half cover the enclosed thermometer bulb.

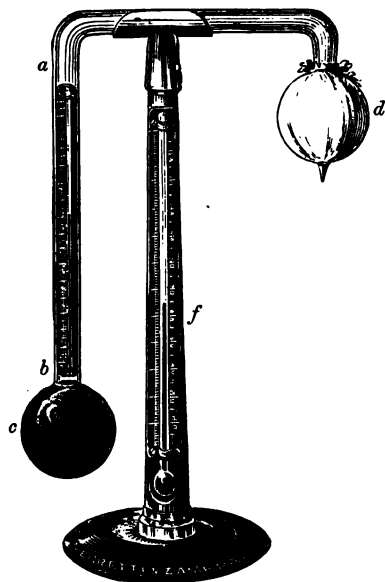


Fig. 79.

Before the tube is sealed up the ether is boiled, so as to drive out the whole of the air. The essential part of the instrument is completed by covering the upper bulb *d* with muslin and gilding a part of the lower bulb. It is now usual, however, to make this lower bulb of black glass. The syphon tube is placed for use upon the little stand to which is attached the second thermometer, *f*, in order that the temperature of the air may be observed at the same time as its dew-point.

To make an observation all the ether within the instrument is first poured into the lower bulb. Then taking a bottle of common ether, a few drops are poured upon the muslin of the upper bulb. Its evaporation cools the bulb, and condenses the ether vapour within. Fresh vapour flows along the bent tube from the lower bulb, and in the manner of Wollaston's cryophorus the temperature of this lower bulb is gradually reduced until the dew-point of the surrounding air is reached, and the dew may be observed forming upon the gilded or blackened surface of the bulb. The dew-point, as shown by the included thermometer, is then to be read, but accuracy is only to be obtained by observing several successive depositions and evaporations of dew in a manner fully described under the head of Regnault's Hygrometer.

The hygrometer of Daniell, however elegant and pleasing, and satisfactory in theory, has many sources of inconvenience and inaccuracy. The expenditure of ether is considerable and costly; and

in a hot and dry climate it is very difficult to obtain any deposition of dew during the long-continued manipulation and close observation of the instrument which is always necessary. The warmth and moisture of the hand and body are sure to affect the indications of both thermometers. The cold ether vapour flowing from the upper bulb may also cause inaccuracy. The last and most important objection is that cold is produced only at the surface of the ether in the lower bulb, and there is no agitation of the liquid to ensure uniformity of temperature. Hence, the internal thermometer may often indicate a temperature some degrees different from that at which dew is being deposited. This objection is partially remedied by making the lower bulb oblique, so that one part of it shall be nearly in contact with the

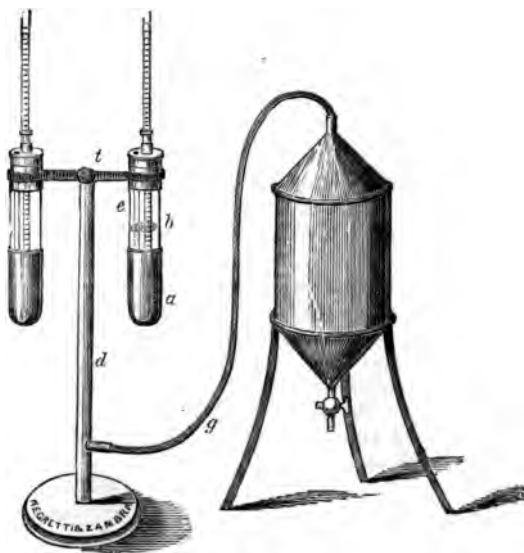


Fig. 80.

thermometer bulb within. Daniell, well aware of this objection, remarks that dew will first be deposited in a circle round the bulb near to the surface of the ether, and directs that the thermometer bulb shall be placed so as to be cut by the surface of the ether.

206. **Regnault's Hygrometer.**—Subsequent to Daniell's in-

vention several dew-point instruments were devised, in which the evaporation of ether was made to cool the bulb of a thermometer and cause a deposit of dew. Among others, that of Regnault may be described as a nearly perfect instrument of its kind. In its complete form, as shown in *fig. 80*, it consists of a very thin and brightly-polished silver thimble *a*, 45 mm. high and 20 mm. in diameter, fitted to the glass tube *b*, which again is fixed by the small lateral tube *t* and the metallic tube *d* to the stand. The upper end of the glass tube *b* is closed by a cork, bearing a thin glass tube *e*, descending nearly to the bottom of the silver thimble, and a very delicate and accurate thermometer, the pear-shaped bulb of which is in the centre of the thimble. A second, exactly similar thermometer, similarly placed within a glass tube and silver thimble, is mounted on the other side of the stand, but the cork need not be penetrated by any glass tube.

To make an observation, so much pure ether is poured into the tube *b* as will rather more than fill the thimble to the level *b*, and the cork being fitted in air-tight the instrument is put in connection, by means of the caoutchouc tube *g*, with a common aspirator, by which an exactly regulated flow of air through the instrument may be obtained. The aspirator, which may have a capacity of 3 or 4 litres is placed close to the observer, and the hygrometer may be at some distance—for instance, outside a window—being observed, if necessary, with a telescope.

Now, when water is allowed to flow from the aspirator, air is drawn through the tube, and, bubbling up through the ether, causes a more or less rapid evaporation. The temperature of the ether is thus slowly reduced, and, from its constant agitation by the stream of air, the silver thimble and the thermometer-bulb are maintained at an exactly similar temperature. After a minute or two at the most, dew will begin to form on the thimble and will be very visible on its brightly polished surface. The thermometer is instantly to be read, and the stream from the aspirator to be stopped. Suppose that the reading observed is $48^{\circ}\cdot 1$ F., the deposit of dew may increase for a few moments, but will soon begin to evaporate again, the thermometer rising.

At the moment that the dew entirely disappears read the thermometer again; let it be $49^{\circ}\cdot 3$. Considering that dew requires a short time to form or evaporate in a visible degree, it is obvious that the dew-point lies between $48^{\circ}\cdot 1$ and $49^{\circ}\cdot 3$. Let an exceedingly slow current of air be now drawn through the ether so that the thermometer is very gradually reduced to $49^{\circ}\cdot 2$, $49^{\circ}\cdot 1$,

49°0, and so on. The point at which dew first appears may now be observed with much greater accuracy ; let it be 48·8. Still it is probable that 48·8 is somewhat below the exact dew-point. If, when the current is stopped, the small deposit of dew vanishes at 49°0, we may consider the mean, or 48·9, to be the true dew-point ; but if necessary we may, by still slower procedure, approximate even more closely. 'All these operations,' observes M. Regnault, 'take more time to describe than to execute ; with a little practice, three or four minutes are sufficient for determining the dew-point almost within $\frac{1}{20}$ th of a degree Centigrade.'

At the same time the second thermometer is to be read, to give the common temperature of the air. From its parallel circumstances and position, its indications would be exactly similar to those of the other ; hence, the difference of the two gives the depression of the dew-point free from almost all kinds of error. It is obvious that all the objectionable points in Daniell's hygrometer are avoided in this admirable instrument. The only remaining objection is the inconvenience of keeping or carrying about a large aspirator, and frequently filling it with water. Mr. Welsh had in the Kew Observatory an aspirator in the form of a circular bellows, to the lower moveable board of which a weight was attached. He also proposed to expand the upper end of the tube *e* into a small funnel, by which fresh ether may readily be introduced.

207. **Psychrometers.** — Daniell's and Regnault's hygrometers belong to the class called condensing hygrometers. A different principle is applied in the so-called *Dry and Wet Bulb Thermometers*, or *Psychrometers*. In these instruments the dew-point is not determined by direct observation, but indirectly. The principle of psychrometers is that a moist body, when the air is dry, evaporates more rapidly than when the air is damp. But in proportion as evaporation on the surface proceeds more rapidly the temperature of the body sinks. Thus, if two thermometers, one having a dry the other a moist bulb, be exposed to dry air, the wet bulb thermometer, on account of the heat it loses by evaporation, will indicate a lower temperature than the dry one, and the difference between the two thermometers will depend on the hygrometric state of the atmosphere, which may be calculated

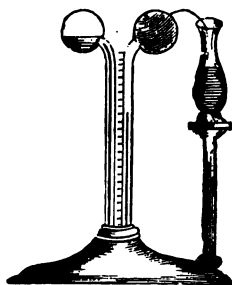


Fig. 8r.

from these observed differences at any time. On this principle the following instruments are based.

208. **Leslie's Thermometric Hygrometer.**

—This instrument, *fig. 81*, is an elementary form of Mason's Dry and Wet Bulb Hygrometer, by which it is now superseded. It consists of a glass tube, terminated with a bulb at each end. The tube is partly filled with sulphuric acid, tinged by carmine. One of the bulbs is covered with muslin and kept constantly moistened with water, drawn from a vase placed near it by the capillary attraction of a few strands of cotton wick. The descent of the coloured liquid in the other stem will mark the diminution of temperature caused by the evaporation of the water from the humid surface. The drier the air is, the more rapidly will the evaporation go on, and the cold produced will be greater. When the air is nearly saturated with moisture the evapo-

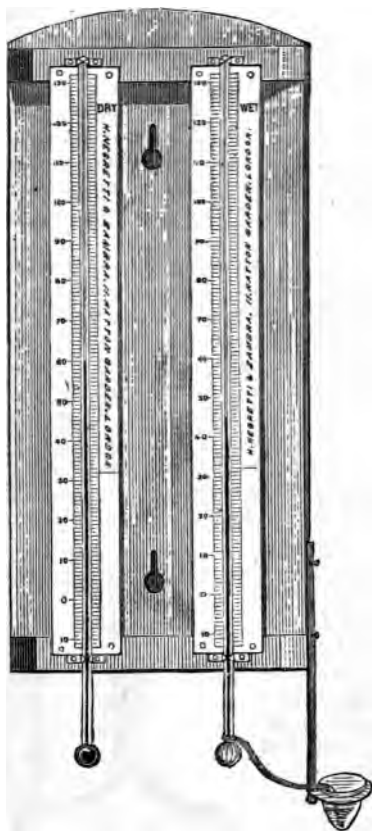


Fig. 82.

ration goes on slowly; the cold produced is moderate, because the bulb regains a large portion of its lost heat from surrounding bodies. The degree of refrigeration of the bulb is an index of the dryness of the air.

209. **Mason's Dry and Wet Bulb Hygrometer.**—This instrument, *fig. 82*, which on the Continent is known as *August's Psychrometer*, consists of two parallel thermometers, as nearly identical as possible, mounted on a wooden bracket, one marked *dry*, the other *wet*. The bulb of the wet thermometer

is covered with thin muslin, round the neck of which is twisted a conducting thread of lamp-wick, or common darning-cotton; this passes into a vessel of water, placed at such a distance as to allow a length of conducting thread of about three inches. The cup or glass is placed on one side and a little beneath, so that the water within may not affect the reading of the *dry bulb* thermometer. In observing, the eye is placed on a level with the top of the mercury in the tube, and the observer should refrain from breathing whilst taking an observation. The temperature of the air and of evaporation is given by the readings of the *two thermometers*, from which the dew-point can be deduced by formulæ or from hygrometric tables.

For practical purposes, in estimating the comparative humidity, the following table (on Fahrenheit's scale), which is reduced from Mr. Glaisher's elaborate tables, will be sufficient.

Temperature by the Dry Bulb Thermometer	Difference between Dry Bulb and Wet Bulb Thermometer					
	2°	4°	6°	8°	10°	12°
	Degree of Humidity					
34	79	63	50	—	—	—
36	82	66	53	—	—	—
38	83	68	56	45	—	—
40	84	70	58	47	—	—
42	84	71	59	49	—	—
44	85	72	60	50	—	—
46	86	73	61	51	—	—
48	86	73	62	52	44	—
50	86	74	63	53	45	—
52	86	74	64	54	46	—
54	86	74	64	55	47	—
56	87	75	65	56	48	—
58	87	76	66	57	49	—
60	88	76	66	58	50	43
62	88	77	67	58	50	44
64	88	77	67	59	51	45
66	88	78	68	60	52	45
68	88	78	68	60	52	46
70	88	78	69	61	53	47
72	89	79	69	61	54	48
74	89	79	70	62	55	48
76	89	79	71	63	55	49
78	89	79	71	63	56	50
80	90	80	71	63	56	50
82	90	80	72	64	57	51
84	90	80	72	64	57	51
86	90	80	72	64	58	52

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The total quantity of aqueous vapour which at any temperature can be diffused in the air being represented by 100, the percentage of vapour actually present will be found in the table opposite the temperature of the dry-bulb thermometer, and under the difference between the dry-bulb and wet-bulb temperatures. The degree of humidity for intermediate temperatures and differences between those given in the table can be easily estimated sufficiently accurately for most practical purposes.

In England the usual difference between the thermometer-readings—in the open air, shaded from the sun, reflected heat, and currents of air—ranges from one to twelve degrees. In hot and dry climates, as India and Australia, the range out of doors has been found as much as 30°.

210. Formulae of reduction. Glaisher's factors.—As already stated, unless the air is saturated with moisture, the wet-bulb thermometer always indicates a lower temperature than the other, and the difference between the indications of the two thermometers is greater in proportion as the air can take up more moisture. The tension, e , of the aqueous vapour in the atmosphere may be calculated from the indications of the thermometer by means of the following empirical formula, in which e' is the maximum tension, corresponding to the temperature of the wet bulb thermometer, h the barometric height at the time, and t and t' the respective temperatures of the dry and wet bulb thermometer:—

$$e = e' - 0.00077 (t - t') h.$$

For example, let $h = 750$ millimetres, $t = 15^\circ \text{C.}$, $t' = 10^\circ \text{C.}$, then according to Table I., page 167, the maximum tension, e' , corresponding to 10°C. is 9.165 millimetres, hence we have

$$e = 9.165 - 0.00077 \times 5 \times 750 = 6.268.$$

Finding from the same table the temperature corresponding to a maximum temperature of 6.278 , we find the dew-point, viz. about $4^\circ.5$. If the air had been saturated at the temperature it has, viz. 15°C. , the tension would have been 12.699 . We may from this conclude that it is about half saturated with moisture.

Although the above formula expresses the result with tolerable accuracy, the constant used in it, 0.00077 , requires to be modified, if the instrument is in different positions. It is correct for a large room with open windows; in small closed rooms it is 0.00128 ; in large rooms it is 0.001 ; and in the open air without wind it is 0.0009 . Regnault found that the difference in temperature of the two bulbs depends on the rapidity

of the current of air ; at a low temperature and in very moist air the results obtained by the psychrometer differed from those given by Regnault's hygrometer.

In this country a formula of reduction, deduced from Dr. Apjohn's investigations, is used. Let F be the elastic force of saturated vapour at the dew-point, f the elastic force at the temperature of evaporation (the wet bulb), d the difference between the dry and wet bulb, and h the barometric pressure in inches of mercury, then

$$F = f - \frac{d}{88} \times \frac{h}{30},$$

when the reading of the wet bulb is above 32° F. ; and

$$F = f - \frac{d}{96} \times \frac{h}{30},$$

when the reading of the wet bulb is below 32° F.

The value of the elastic force in inches has been given for successive temperatures expressed in Fahrenheit's degrees, in Table I., page 165, but it will be more convenient for the present purpose to use Table I. given on next page, which is taken from Mr. Glaisher's Hygrometric Tables. From this table f is found, and d and h being obtained by observation, F is calculated. The dew-point is then found by using the table reversely, that is by finding the temperature corresponding to the elastic force F , as calculated by the above formula. To take an example :—Suppose the dry bulb to read 50° and the wet 45° , the barometer standing at 29 inches. Then f , from Table I. below, is found = .299 inch, hence

$$F = .299 - \frac{50 - 45}{88} \times \frac{29}{30} = .244.$$

From Table I. again we find the temperature of the dew-point opposite .244 to be $39^{\circ}.7$, which is therefore the temperature of the dew-point when the dry bulb is 50° and the wet bulb 45° .

To obviate such laborious calculations Mr. Glaisher has elaborated a series of *factors* from the combination of simultaneous observations of the dry and wet bulb thermometers with Daniell's hygrometers. These factors are given in Table II. below. We shall find the dew-point of the above example by them. The factor opposite the dry bulb 50° is 2.06, and the difference between the two thermometers is 5° , therefore

$$2.06 \times 5 = 10.3,$$

hence dew-point = $50 - 10.3 = 39^{\circ}.7$, as before.

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TABLE I.—*Showing the Elastic Force of Aqueous Vapour, in inches of Mercury from 0° to 80°, calculated from the Experiments of Reynault. From Mr. Glaisher's Hygrometric Tables.*

The intermediate tenths of degrees may be easily interpolated.

Temp.	Force of vapour	Temp.	Force of vapour	Temp.	Force of vapour	Temp.	Force of vapour
°	Inch	°	Inch	°	Inch	°	Inch
0	·044	33·5	·192	43·7	·285	53·0	·403
1	·046	34·0	·196	44·0	·288	53·3	·407
2	·048	34·5	·199	44·3	·292	53·5	·410
3	·050	35·0	·204	44·5	·294	53·7	·413
4	·052	35·3	·206	44·7	·296	54·0	·418
5	·054	35·5	·208	45·0	·299	54·3	·422
6	·057	35·7	·209	45·3	·303	54·5	·425
7	·060	36·0	·212	45·5	·305	54·7	·428
8	·062	36·3	·214	45·7	·307	55·0	·433
9	·065	36·5	·216	46·0	·311	55·5	·441
10	·068	36·7	·218	46·3	·315	56·0	·449
11	·071	37·0	·220	46·5	·317	56·5	·457
12	·074	37·3	·223	46·7	·319	57·0	·465
13	·078	37·5	·225	47·0	·323	57·5	·473
14	·082	37·7	·226	47·3	·327	58·0	·482
15	·086	38·0	·229	47·5	·329	59·0	·500
16	·090	38·3	·231	47·7	·331	60·0	·518
17	·094	38·5	·233	48·0	·335	61·0	·537
18	·098	38·7	·235	48·3	·339	62·0	·556
19	·103	39·0	·238	48·5	·342	63·0	·576
20	·108	39·3	·240	48·7	·344	64·0	·596
21	·113	39·5	·242	49·0	·348	65·0	·617
22	·118	39·7	·244	49·3	·352	66·0	·639
23	·123	40·0	·247	49·5	·355	67·0	·661
24	·129	40·3	·250	49·7	·357	68·0	·684
25	·135	40·5	·252	50·0	·361	69·0	·708
26	·141	40·7	·254	50·3	·365	70·0	·733
27	·147	41·0	·257	50·5	·367	71·0	·759
28	·153	41·3	·260	50·7	·370	72·0	·785
29	·160	41·5	·262	51·0	·374	73·0	·812
29·5	·163	41·7	·264	51·3	·378	74·0	·840
30·0	·167	42·0	·267	51·5	·381	75·0	·868
30·5	·170	42·3	·270	51·7	·384	76·0	·897
31·0	·174	42·5	·272	52·0	·388	77·0	·927
31·5	·177	42·7	·274	52·3	·393	78·0	·958
32·0	·181	43·0	·277	52·5	·396	79·0	·990
32·5	·184	43·3	·280	52·7	·399	80·0	1·023
33·0	·188	43·5	·283				

TABLE II.—*Factors for Multiplying the Excess of the Dry-bulb Thermometer over that of the Wet-bulb, to find the Excess of the Temperature of the Air above that of the Dew-point. From Mr. Glaisher's Hygrometric Tables.*

Dry-bulb Ther.	Factor	Dry-bulb Ther.	Factor	Dry-bulb Ther.	Factor	Dry-bulb Ther.	Factor	Dry-bulb Ther.	Factor
10	8.78	28	5.12	46	2.14	64	1.83	82	1.67
11	8.78	29	4.63	47	2.12	65	1.82	83	1.67
12	8.78	30	4.15	48	2.10	66	1.81	84	1.66
13	8.77	31	3.70	49	2.08	67	1.80	85	1.65
14	8.76	32	3.32	50	2.06	68	1.79	86	1.65
15	8.75	33	3.01	51	2.04	69	1.78	87	1.64
16	8.70	34	2.77	52	2.02	70	1.77	88	1.64
17	8.62	35	2.60	53	2.00	71	1.76	89	1.63
18	8.50	36	2.50	54	1.98	72	1.75	90	1.63
19	8.34	37	2.42	55	1.96	73	1.74	91	1.62
20	8.14	38	2.36	56	1.94	74	1.73	92	1.62
21	7.88	39	2.32	57	1.92	75	1.72	93	1.61
22	7.60	40	2.29	58	1.90	76	1.71	94	1.60
23	7.28	41	2.26	59	1.89	77	1.70	95	1.60
24	6.92	42	2.23	60	1.88	78	1.69	96	1.59
25	6.53	43	2.20	61	1.87	79	1.69	97	1.59
26	6.08	44	2.18	62	1.86	80	1.68	98	1.58
27	5.61	45	2.16	63	1.85	81	1.68	99	1.58
								100	1.57

In every case, by the two observations, viz., the temperature of the air, as shown by the dry bulb, and the temperature of evaporation, as shown by the wet bulb—or by determining the dew-point directly by means of a hygrometer of condensation—the following physical numerical data may be determined :—

- (1) The dew-point.
- (2) The elastic force of vapour, or the amount of barometric pressure due to the vapour present in the atmosphere.
- (3) The quantity of aqueous vapour in a cubic foot of air.
- (4) The additional vapour required to saturate a cubic foot of air.
- (5) The relative humidity.
- (6) The weight of a cubic foot of air at the pressure prevailing at the time of observation.

Examples on the calculation of some of these data will be given in the next chapter.

211. Precautions in using the dry and wet bulb hygrometer.—Some precaution is required in taking the observations when the temperature of the air is below 32° . In such cases, if the wet bulb reads higher than the dry bulb, as sometimes happens, the observation is clearly valueless, the instrument being for the time not in proper working order. If the water on the muslin be frozen, the readings are quite good, since evaporation takes place from ice as well as from water. But if the muslin be dry it must first be wetted, and then allowed to freeze before the observation is taken. A useful rule to observe in frosty weather is to immerse the bulb and conducting-thread in water after every observation, by which sufficient ice will still be adhering to the muslin at the time of the next observation. When the temperature of the air rises above 32° , the wet bulb must be plunged into warm water to melt any ice that may remain on it, after which it must be allowed sufficient time to cool before being observed.

To keep this instrument in working order one or two points require to be attended to. Both thermometers must be exactly alike, and of the same kind; for if one is filled with mercury and the other with alcohol, or if they contain different quantities of the same fluid, the readings will in either case be vitiated. All starch or foreign matter should be washed out of the muslin and cotton. The water used should be pure; for if lime be dissolved in it, the muslin will soon be coated with a calcareous incrustation. Rain or distilled water should be used. The muslin ought to be changed when covered with dust or other impurities, and care should be taken not to touch the muslin with the fingers, otherwise it will get slightly greased, and capillary attraction be interfered with. The bulbs of the two thermometers should be made to project one and a half or two inches below the scales; the thermometers should also be a little apart from each other, and the glass vessel, as already stated, be as far as possible from the dry bulb.

212. Indications of hygrometers are essentially local.—If the vapour of water remained permanently in the atmosphere, that is, if it were not liable to be withdrawn from it by being condensed into rain, snow, hail, &c., the amount would vary from time to time, but at any time the mixture of vapour and air would be as complete and uniform as that of the oxygen and nitrogen. But the equilibrium of the vapour atmosphere is being constantly disturbed by every instance of condensation,

by the ceaseless process of evaporation, and by every change of temperature. From this it may easily be inferred that an equal diffusion of the vapour, even over a comparatively small area, can hardly ever take place. The law of the independent pressure of the vapour, and of the dry air of the atmosphere, can thus not hold good in general, although there is a constant tendency to approach a state of equal diffusion. But since such a state is never reached, the observations of the hygrometer only indicate local humidity. Hence they should never be regarded as anything more than approximations to the quantity of vapour in the atmosphere over the place of observation. Nevertheless, though in particular cases the amount of vapour indicated by the hygrometer may be wide of the mark, yet in long averages a close approximation is obtained, except in confined localities which are exceptionally damp or exceptionally dry.

213. Practical bearing of the dew-point.—As Mr. Buchan, the distinguished scientific meteorologist, has pointed out, the ascertaining of the dew-point is of great practical importance, particularly to horticulturists, since it indicates the point near which the descent of the temperature of the air during the night will be arrested. For when the air has been cooled down by radiation to this point, dew is deposited and latent heat given out. The amount of heat thus set free being great, the temperature of the air is immediately raised. But as the cooling by radiation proceeds the air again falls to, or slightly under, the dew-point, dew is now again deposited, heat liberated, and the temperature raised. The same process continues to be repeated, and thus the temperature of the air in contact with plants and other radiating surfaces may be considered as gently oscillating about the dew-point. For if it rises higher, the loss of heat by radiation speedily lowers it, and if it falls lower by ever so little, the liberation of heat, as the vapour is condensed into dew, as speedily raises it. Thus then the dew-point determines approximately the minimum temperature of the night. This suggests an important practical use of the hygrometer. If the dew-point be ascertained the approach of low temperatures or of frost may be foreseen and provided against. Thus, suppose on a fine clear spring day, towards evening, that the dry bulb was 50° and the wet 40° , the dew-point at the time is therefore $29^{\circ}4$. Frost on the ground may then be predicted with certainty, and no time ought to be lost in protecting such tender plants as may be exposed in the open air. If, on the other hand, with a sky quite as clear, the dry bulb was 50° and the

wet 47° , the dew-point being in this case $43^{\circ}8$, no frost need be apprehended. The raising or depressing of the dew-point during the night by a change of wind is the only circumstance that can happen to interfere with predictions founded on the hygrometer.

214. **Other hygrometric instruments.**—Besides the hygrometers of condensation, and those of evaporation, which have been described in the previous articles, instruments have been devised for determining the relative humidity of the air, based on other principles.

Some of these are founded on the property which some organic substances have of elongating when exposed to moist air, and of again contracting as they become dry. Saussure's hygrometer is the most common form, although it has never been used for scientific purposes out of France. It consists of a brass frame along which a hair is fixed; the upper end of the hair is fastened in a clamp provided with a screw, while the lower portion of the hair passes round a pulley and supports a small weight. On the pulley there is a needle which moves along a graduated scale. When the hair becomes shorter, in a dry state of the air, the needle rises, when it becomes longer the weight attached to the hair makes the needle move in the opposite direction.

At best such an instrument indicates only opposite states, but can give no indication as to the quantity of vapour present. To the same class belongs the small apparatus, formerly much used as a chimney ornament, being a small male and female figure, so arranged in reference to a little house with two doors, that when it is moist the man goes out and the woman goes in, and *vice versa* when it is fine. This contrivance is founded on the property which twisted strings or pieces of catgut possess, of untwisting when moist and of twisting again when dry.

Instruments of this kind are usually called hygrometers of absorption, or better *hygroscopes*.

Chemical hygrometers are the only instruments for measuring directly by experiment the amount of moisture in a given volume of air. The method consists in passing a known volume of air over a substance which readily absorbs moisture—chloride of calcium, for instance. The substance having been weighed before the passage of the air, and again afterwards, the increase in weight represents the amount of aqueous vapour present in the air. Although the correctness of the results obtained by this method is irreproachable, yet each experiment involves so many manipulations requiring much time, and so

much practical experience and care, that it is unsuitable for continued observations on the changes in the hygrometric state of the air.

CHAPTER X.

CHEMICAL EFFECTS OF HEAT.

215. **Dissociation.**—When a few small crystals of blue vitriol are gently heated in a dry narrow glass tube, or in a watch-glass heated on a sand-bath, they turn into a white powder, while the colder parts of the tube are coated with drops of water. Blue vitriol is thus, by the action of heat, broken up into water and a white substance. If to this latter substance, after it is cooled, a few drops of water are added, the white colour is again changed to the original blue, and much heat is evolved during this change; so that a small thermometer, introduced into the powder, would rise very considerably as soon as the water is added, both substances and the thermometer being previously at one and the same temperature, viz., that of the surrounding air.

This action of heat is different from both fusion and vapourisation. Here the change of state of bodies induced by heat is not a physical change but a chemical change; the white powder and the water, which result from the action, were previously to it chemically combined in the blue vitriol, and it is solely due to the effect of heat that two different bodies have been produced. This action is termed *dissociation*, because the one substance (blue vitriol) was decomposed into water and the white powder, and both these latter substances were thus dissociated.

The white powder which remains is termed anhydrous copper sulphate, for it can be obtained from copper and sulphuric acid. Hence blue vitriol consists of copper sulphate and water. Substances like the blue vitriol which contain water are termed hydrated. The white powder and the blue vitriol differ therefore solely in this, that the former is anhydrous and the latter hydrated copper sulphate. The water in the blue vitriol is essential to the crystalline form of the latter, for the experiment shows that the expulsion of the water also destroyed the crystalline form. Hence such water is often termed *water of crystallisation*, and it can always be expelled by proper heating. All crystal-

lised substances which contain water of crystallisation may therefore be dissociated, that is, they can be decomposed by heat alone : the water of crystallisation will be expelled, and an anhydrous residue will remain. Some substances—for example, alum, borax, and others—first apparently fuse when heated, but the fusion lasts only as long as they yield up their water of crystallisation ; when all the water has been expelled, the white residue remains solid, and is generally infusible. The fusion in the water of crystallisation is termed *aqueous fusion* ; the true fusion is distinguished from it as *igneous fusion*.

The dissociation of the blue vitriol may be carried farther than the separation of the water of crystallisation. If pulverised blue vitriol is heated on a small platinum dish or porcelain capsule, directly over the flame of a suitable gas burner, so as to be exposed to a red heat, it will rapidly turn white by the above dissociation and continue to change in colour through brown to black. The black substance remaining is called copper oxide, and may be simply obtained by heating copper in a flame. The white powder has thus lost something by further heating, which may be termed anhydrous sulphuric acid, that is further dissociation has taken place. At this stage, however, there is a limit reached to the further action of heat alone, for by merely heating the black copper oxide it has not yet been further dissociated. However, it is not doubted that exposure to a sufficiently high temperature will dissociate it again, leaving metallic copper ; but, as stated, this dissociation has so far never been accomplished.

216. **General chemical effects of heat.**—It will be seen from the preceding experiments that heat appears in general to have a tendency to counteract that force by which chemical compounds are supposed to be formed and their constituents held together ; in other words, that heat and chemical affinity have an antagonistic relation to each other. While on one hand chemical compounds are dissociated by heat alone, the latter part of the first experiment proves, that on the other hand heat is produced when chemical compounds are formed by the combination of their constituents. The conclusions to which the above experiments would lead are, however, by no means generally correct, as will be seen farther on. Of late years considerable attention has been given to those relations existing between chemical action and the manifestation of that force we call heat ; and as the fundamental result of these investigations, it may be stated generally that *no chemical action whatever takes place without development or absorption of heat*. From certain

principles, which will be discussed farther on in the chapter on the nature of heat, it will become apparent that if there be no manifestation of any other force, such as electricity or light, or any change in the physical conditions of the substance, as from the solid to the liquid or gaseous state, the amount of heat developed must be the true measure of the chemical action, thus furnishing an accurate means of ascertaining the amount of force put in operation in different cases of chemical action, and consequently of comparing them with one another. At present, however, owing to the many complications introduced by physical changes, only a comparatively few simple relations have been anything like thoroughly investigated.

In order to compare the results some standard unit must be employed ; that which is generally adopted in these investigations is the amount of heat necessary to raise one gramme of water 1°C. , usually termed the Gramme-Degree thermal unit (see Art. 95, p. 97). Thus 100 grammes of water raised 10°C. , or 200 grammes raised 5°C. , or 250 grammes raised 4°C. , would each represent 1000 thermal units. Many of the effects of heat, however, do not as yet admit of measurement.

217. Influence of temperature on chemical attraction.—Elevation of temperature frequently augments the tendency to combination between bodies which are submitted to its influence : for example, sulphur or charcoal may be preserved for an indefinite period at ordinary temperatures in air or in oxygen, without change ; but if sulphur be heated to 260°C. , and charcoal to a point a little below a red heat, oxidation commences, and proceeds with such energy that the substance inflames. It not unfrequently happens, however, that a moderate elevation of temperature produces combination, whilst a higher temperature destroys the compound so formed ; as, for example, in the action of oxygen upon mercury. At ordinary temperatures this metal shows no disposition to combine with oxygen, for it evaporates in air and becomes condensed again in the metallic form ; but at a temperature approaching 370°C. , or a little above the boiling point of the metal, it combines gradually with oxygen, and becomes converted into the red oxide ; whilst at a somewhat higher temperature it is again decomposed into gaseous oxygen and vapour of mercury. Again, baryta at a red heat absorbs a second atom of oxygen, forming baric peroxide, but the second atom of oxygen is expelled again by a full white heat, and the compound is reconverted into baryta. A mixture of oxygen and hydrogen may be preserved unchanged at ordinary temperatures, but the introduction of a glass rod

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metals rapidly in solution or immediately alters their mutual attraction that sudden combination attended with explosion is the result. This appears to be as pure a case of augmentation of chemical attraction as can be met with, since both the components are thoroughly mixed, and as both are perfect gases, heat cannot in this case act by diminishing cohesion, and so bringing their particles into more intimate contact. Grove, however, has shown that in the case of this same compound of oxygen and hydrogen, a sudden increase of chemical attraction takes place, for at an intense white heat water is resolved into its constituent gases. The experiment may be made either by the rapid ignition of a platinum wire under water, or by the intense heat of a ball of melted platinum raised to whiteness by an alcohol flame assisted by a current of oxygen and then plunged under water: in both cases the portion of water in immediate contact with the metal is resolved into its elements, and the mixed gases may be collected.

212. *Influence of heat on chemical separation.*—Although, as has been shown in the preceding instances, elevation of temperature frequently assists combination, yet in many instances it has quite the opposite effect; as, for example, in the experiment with blue vitriol. This action of heat is no doubt due to a great extent to the mechanical effect of heat in separating the ultimate atoms of which matter is composed, and from the greater freedom of motion amongst the particles, permitting the atoms to rearrange themselves in new and more stable combinations; the degree of mobility varying with the temperature. For example, olefiant gas at a full red heat loses half its carbon, and is converted into light carburetted hydrogen; and this gas, if subjected to a white heat, deposits the remainder of its carbon, leaving pure hydrogen. Potassic chlorate at a moderate heat is decomposed into perchlorate, and probably into chlorite; the latter salt, however, is immediately resolved into oxygen, and the more stable potassic chloride is the final result. Organic chemistry especially abounds in instances of this kind. A further illustration of this point is afforded by the different products which are furnished by the combustion of the same body at different temperatures. When a jet of cyanogen is burned with a free supply of air, the only products of the combustion are carbonic acid and nitrogen; but if a coil of red-hot platinum wire be suspended in a mixture of equal volumes of cyanogen and oxygen, the nitrogen undergoes oxidation as well as the carbon, nitric oxide being formed, as is shown by the appearance of ruddy fumes, owing to the combination of the nitric

oxide with free oxygen. In a similar manner, ether, when burnt freely in air, produces carbonic acid and water ; but if a glowing coil of platinum wire be suspended in a mixture of ether and atmospheric air, several new products are formed, among which are aldehyd and acetic acid.

219. **Dissociation of gaseous compounds.** — When a rapid current of carbonic acid, mixed with steam, is transmitted through a porcelain tube of 2 inches or $2\frac{1}{2}$ inches in diameter, which has been filled with clean and previously ignited fragments of porcelain, and the tube is heated intensely in a blast-furnace or forge, it is found that the gas which is left, after absorbing the excess of carbonic acid by means of caustic potash, consists of an explosive mixture of oxygen, hydrogen, carbonic oxide, and nitrogen. Water has here been decomposed into its constituents, part of the liberated hydrogen has exerted a reducing action on the carbonic acid, and part of the hydrogen has escaped re-oxidation by its copious dilution with other gases. The presence of nitrogen is due to the entrance of atmospheric air ; for however carefully the gases are prepared, it is nearly impossible, in an experiment of this kind, which lasts for a couple of hours, to exclude the air perfectly. A still larger proportion of the explosive mixture is obtained by placing a tube of porous earthenware in the axis of a shorter but wider tube of glazed porcelain, fitting them air-tight with corks, and passing a current of any gas at pleasure through the inner tube, and through the interval between the two tubes. By a suitable arrangement of glass tubes, the gases may be collected from either tube separately, and the effects of heating the tubes can be observed upon the issuing gases. For example, if the tube be heated to from 1100° to 1700° C., and a current of steam be passed through the inner tube, whilst carbonic acid is passed through the outer tube, an explosive mixture, similar to that already described, is obtained, but in larger quantity. The hydrogen, at the moment that it is liberated by the effect of heat from its combination with oxygen, at once becomes diffused through the porous tube into the outer one, and there reduces the carbonic anhydride, whilst the less diffusible oxygen passes on. In like manner, if a brisk current of pure carbonic acid be passed through a porcelain tube filled with fragments of porcelain, and the temperature be raised to 1300° C., after absorbing the carbonic acid, a mixture of two volumes of carbonic oxide and one of oxygen, with a little nitrogen, is obtained. It is this kind of partial decomposition at elevated temperatures for which Deville proposed the name of dissocia-

tion. During the occurrence of this phenomenon an absorption of heat takes place, exactly corresponding to the force necessary to overcome the chemical attraction of the two elements. The dissociation of compound gases has been carried still farther. Carbonic oxide may be resolved into carbon and carbonic acid by the following arrangement:—A porcelain tube is placed across a furnace, the temperature of which can be raised very high. In the axis of this tube is supported a thin brass tube of about one-third of an inch in diameter, through which a current of water is kept flowing. Through the outer tube a current of pure carbonic oxide is maintained, transmitting from 4 to 6 litres (from 250 to 350 cubic inches) of the gas per hour. The porcelain tube is gradually raised to bright redness, and on causing the escaping gas to pass through baryta water, a precipitate of baric carbonate is gradually formed, and a layer of black carbon is deposited upon the under surface of the brass tube, where the current of ascending heated gas strikes against the cooled metal. A similar decomposition may be effected by passing a succession of electric sparks through carbonic oxide over mercury, upon which a few drops of concentrated solution of potassic hydrate have been placed to absorb the carbonic acid as it is formed.

When instead of carbonic oxide pure and dry sulphurous acid is passed through the porcelain tube, the gas becomes partially resolved into sulphur and sulphuric acid (anhydrous). The interior metallic tube in this case was made of copper thickly plated with a voltaic deposit of silver. If this tube be amalgamated, and a current of pure and dry hydrochloric acid gas be passed through the ignited porcelain tube, heated to at least 1500°C ., whilst the temperature of the metallic tube is reduced below 50° , a deposit of chloride of mercury and chloride of silver is formed in a few hours, and a small quantity of hydrogen may be collected. Decomposition of hydrochloric acid gas may be effected to a small extent by the continuous discharge of electric sparks for three or four days through the dry gas, and with sulphurous acid the experiment is very easy. Carbonic acid is also readily decomposed by the heat of the electric spark if a little piece of phosphorus is passed up into the tube to absorb the oxygen as fast as it is liberated.

220. Retardation of chemical action by lowering the temperature.—Whilst, on one hand, elevation of temperature tends to increase chemical attraction, so, on the other hand, chemical attraction is diminished by reduction of temperature. It has been shown by Schrötter, that by a sufficient degree of

cold, chemical combination may be prevented even between bodies which at the ordinary temperature of the air unite with each other with great energy. Chlorine, for example, combines with phosphorus, or with finely-divided metallic antimony or arsenicum, with such violence that these bodies take fire spontaneously in an atmosphere of the gas ; but if the chlorine be cooled down to -76°C , by means of a bath of solid carbonic acid and ether, it remains liquid at the ordinary pressure of the air, and it is then quite indifferent to phosphorus, arsenicum, or antimony, provided these substances be cooled to the same temperature before they are introduced into the liquid chlorine. When the tube in which the mixture is contained is withdrawn from the cold bath, the evaporation of the chlorine occurs with sufficient rapidity to preserve the temperature below the point of combination ; but if the free escape of the chlorine be prevented, the temperature rises and combination occurs with explosive violence. The mutual action of other substances of great mutual affinity—for example, of chlorochromic acid and alcohol, of chlorine and ammonia, of iodine or of bromine and phosphorus, and various other attractions of a similar kind—may be prevented in the same way.

From the experiments described in this and the preceding article, we may infer the following principle as most probably generally true. When two bodies have a chemical attraction for each other, there is a certain range of temperature within which they will enter into combination ; but if the temperature be raised or depressed beyond a certain limit, their mutual attraction is suspended, and at high temperatures the compound already formed may be destroyed. The temperature most favourable for combination varies with each pair of bodies, and it seems to be probable that there is for each a certain temperature in which the maximum of attraction exists, and above and below which it decreases.

221. General remarks on dissociation or thermolysis.

—The relations of heat and chemical action, as has already been stated, may be classified under two distinct heads. 1st, Heat induces, modifies, or destroys chemical affinity. 2nd, Chemical action is a source of heat. Some of the phenomena belonging to the first class of phenomena have been described in the preceding articles ; but for a more extended insight into them the student must consult larger works on chemistry, such as Miller's 'Chemistry' and Watts' 'Dictionary of Chemistry,' from both of which the facts contained in this chapter have been principally gleaned. The phenomena in which chemical

action is a source of heat will be described farther on. The term 'dissociation' was originally applied to signify the separation of a compound into its elements, ultimate or proximate, by the agency of heat alone. It has sometimes been used, as previously mentioned, to denote more especially those decompositions by heat in which only a partial separation of the constituents takes place; but the original signification is the most convenient, and is most generally adopted. As, however, 'dissociation' might be applied equally well to the separation of a mass into its constituent particles, similar or dissimilar, by mechanical or any other means, it has been proposed to replace it by the more specific term *Thermolysis*.

An essential condition of thermolysis is that one or both the constituent elements be capable of assuming the gaseous state; compounds like borates and silicates, both whose constituents are fixed in the fire, are never decomposed by heat alone. Another essential condition of thermolysis is that the constituents of the compound shall, in combining, have given out heat; and the process of thermolysis consists in restoring to the elements the heat which they have lost in combination. When 1 gramme of hydrogen gas unites with 8 grammes of oxygen to form water, a quantity of heat is evolved capable of raising the temperature of 34,462 grammes of water by 1° C., the two gases and the water produced being supposed to be at the temperature of 0° C. Whence is this heat derived? It did not pre-exist in the gases as heat, at least not as sensible or communicable heat; but the gases in combining have lost that peculiar movement of their atoms and molecules which is the essential condition of the gaseous state, and have been converted into the much less volatile compound—water. Now it is just this quantity of motion which, in the act of combination, is converted into sensible heat, amounting to 34,462 thermal units; and if the water is to be resolved into its constituents, these 34,462 units of heat must be restored to the elements, and reconverted into the kind of motion which is essential to the gaseous state.

Another feature of thermolysis is that it takes place with greater facility in proportion as the elements of a compound differ more widely from one another in their chemical characters; thus the antimonide of hydrogen is decomposed by heat more easily than the arsenide, and this more easily than the sulphide. The oxides of the noble metals are very easily resolved into their elements by heat. When such an oxide is reduced by hydrogen, less heat is produced than when the

hydrogen combines with free oxygen, because the latter, in its state of combination as oxide, has lost its gaseous form and the molecular movement belonging thereto. The peroxides of lead and manganese are resolved by heat into free oxygen and lower oxides; and it is conceivable that at a higher temperature they might be resolved into oxygen and metal. Carbon disulphide is resolved, by the heat of an electro-ignited platinum-spiral, into sulphur and carbon, the decomposition being, however, attended, not with absorption, but with emission of heat. This apparent anomaly is explained by the fact that the carbon and sulphur, in combining together at a white heat, pass from the solid to the gaseous state, and absorb heat. A gramme of carbon disulphide in burning in oxygen develops 222 units more than its elements in the free state; it must, therefore, in the act of combination, have taken up molecular movement, and it is in consequence of this that the compound is much more volatile than either of its constituents. The main points in the theory of thermolysis may be summarised as follows:—

1. Thermolysis, or dissociation, is the process opposite to chemical combination; the gaseous constituent of the compound resuming its molecular movement in the form of heat, and transforming it into a new form of movement which it had lost in the act of combination.
2. The quantity of heat taken up by the separated constituents is equal to that which they had lost in combining.
3. Compounds not containing any volatile constituent cannot be decomposed by heat.

CHAPTER XI.

APPLICATIONS OF THE PRECEDING PRINCIPLES (INCLUDING PROBLEMS.)—A. EXPANSION.

222. Practical calculations involving the use of coefficients of linear expansion.

1. The linear magnitude of a body at 0° is L ; at t° it is L' . What is the coefficient of linear expansion of the substance of the body?

$$\text{Coefficient of expansion} = \frac{L' - L}{t \cdot L}$$

2. The length of a wrought-iron rail at 0° is 2.5 metres; what is its length at 30° C.?

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The coefficient of linear expansion being in this case $= 0.000011$, we shall have

$$\begin{aligned}\text{length of bar at } 30^\circ &= 2.5 (1 + 0.000011 \times 30) \\ &= 2.50083 \text{ metres.}\end{aligned}$$

3. A rod of zinc at 0°C. is $.3$ metres long; find its length at 40°C.

The coefficient of linear expansion of zinc being $= 0.00003$,

$$\begin{aligned}\therefore \text{length of bar at } 40^\circ &= .3 (1 + 0.00003 \times 40) \\ &= 0.3004 \text{ metres.}\end{aligned}$$

4. The length of the bar at t° is L , the coefficient of expansion being a . What will be the length of the bar at t'° ?

the length is found from the proportion :

$$L : x :: 1 + at : 1 + at'$$

$$\therefore \text{length at } t'^\circ = L \frac{1 + at'}{1 + at}.$$

From this formula, by actually dividing, we obtain the length

$$\text{at } t'^\circ = L \left(1 + a \frac{(t' - t)}{1 + at} \right);$$

or, neglecting at , which is a very small quantity if the temperature lies between 0° and 100° , we obtain

$$\text{length at } t'^\circ = L (1 + a(t' - t)),$$

which is more easily calculated and very approximately correct.

5. A brass rod is $.5$ metre long at 40°C. ; what will be its length at 0°C. ? Let x be the required length at 0° .

$$\begin{aligned}\text{From } 0.5 &= x (1 + 0.0000192 \times 40) \text{ follows} \\ x &= 0.499616 \text{ metre.}\end{aligned}$$

6. What must be the length of a brass rod at 15°C. in order that at 0°C. it may be exactly 2 metres long?

$$x = 2 (1 + 0.0000192 \times 15) = 2.000576 \text{ metres.}$$

7. A tube of cast iron is 2 metres long at 20°C. What will be its length at 100°C. ?

$$x = 2 (1 + 0.000011 \times 80) = 2.00176 \text{ metres}$$

approximately, using the shorter formula of (4).

8. A glass rod has a length of 2 metres at 25°C. ; find its length at 400°C.

By the first formula of (4) we shall have :—

$$x = 2 \left(\frac{1 + 0.00000861 \times 400}{1 + 0.00000861 \times 25} \right) = 2.006456 \text{ metres.}$$

9. A bar of metal, 7 metres long, expands exactly as much as a bar of another metal which is 9 metres long, when both are heated through the same range of temperature. If the coefficient of expansion of the first metal is $= \frac{1}{735}$, what is the coefficient of expansion of the second metal?

Let κ be the co-efficient of expansion of the second metal, then :

$$\kappa \times 9 = \frac{1}{735} \times 7$$

$$\kappa = \frac{7}{9 \times 735} = \frac{1}{945}$$

10. A bar of metal, of which the coefficient of linear expansion is $\frac{1}{754}$, has at 0° a length of 2 metres. What length must another bar have, made of a metal of which the coefficient of expansion is $\frac{1}{1150}$, in order that both bars may expand equally for one degree of elevation of temperature?

If l be the length of the second bar, then

$$l \times \frac{1}{1150} = 2 \times \frac{1}{754}$$

$$l = 3.050 \text{ metres.}$$

11. At a given temperature an iron pendulum of length 3.167 feet beats seconds; how many oscillations less per day will it make when the temperature has risen 20°C .?

In general, let L = the length of the pendulum beating seconds, and let in consequence of expansion the length L be increased by a small quantity $= d$; how many oscillations less will it now make per day?

Let the number of oscillations per day, viz. 86400, made by a correct pendulum, be denoted by N , and the number of oscillations made less per day by the elongated pendulum be denoted by n . Now it is shown in the treatise on MECHANICS in this series (see chap. on the Pendulum), that the lengths of two pendulums are in the inverse ratio of the squares of the number of oscillations made by them in the same time. Hence,

$$L + d : L :: N^2 : (N - n)^2, \text{ or}$$

$$\frac{L + d}{L} = \frac{N^2}{(N - n)^2} = 1 + \frac{2n}{N} + \dots \quad (\text{by division})$$

Neglecting the higher powers of $\frac{n}{N}$, we may take

$$\frac{L + d}{L} = 1 + \frac{2n}{N} \therefore n = \frac{dN}{2L}$$

Substituting the proper values given in the above particular case, and considering that the increase in length of the pendulum is equal to the length, multiplied by the increase in temperature and by the coefficient of expansion of iron, we obtain

$$n = \frac{(3.167 \times 0.000011 \times 20) 86400}{2 \times 3.167} \\ = 9.504 \text{ oscillations.}$$

12. A circular disc of iron (coefficient of linear expansion = 0.0000122) has at 0° a diameter of 2.75 metres. What will be the surface of the disc at 60° C. ?

If s = the surface at 60°, then by geometry :

$$s = \pi r^2, \text{ } r \text{ being the semi-diameter, and } \pi = 3.1416.$$

But if R = semi-diameter at 0°, then

$$r = R (1 + 0.0000122 \times 60)$$

$$s = 3.1416 (1.375)^2 (1 + 0.0000122 \times 60)^2$$

or, $s = 5.9483 \text{ square metres.}$

223. **Compensation of pendulums for temperature.**—The variation of temperature involves a lengthening or shortening of the pendulums of clocks, and as will be seen from problem (11) in the preceding article, an alteration of the rate. In the better kinds of clocks the variation of temperature is guarded against by the use of what is called a compensation pendulum. A common form is Harrison's gridiron pendulum, shown in *fig. 83*. Its construction depends on the principle of the *unequal* rate of expansion of different metals. If a pendulum were constructed with a single metallic rod, its rate of vibration would constantly change with every alteration of temperature ; but by a combination of steel and brass rods, s , B , arranged alternately, and of such length that the expansion or contraction of the steel rods may be exactly neutralised by the contraction or expansion of the brass ones, the influence of variation of temperature may be excluded. To understand the action of the pendulum, let o be its centre of oscillation, that is, let $A o$ represent the length of an equivalent simple pendulum beating correctly seconds. With a rise of temperature, and especially throughout the summer, the steel rods will expand,

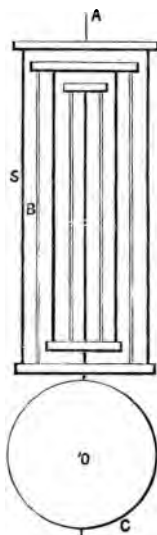


Fig. 83.

but they are so fixed that in expanding the bob *c* is carried downwards, the centre bar of steel passing freely through the two crossbars below, but being fixed securely above. The consequence is that the point *o* is lowered exactly by a quantity which depends on the length of the bars, the coefficient of linear expansion of steel, and the rise of temperature. But the brass rods also expand, and since they are securely fixed above and below, when they expand the effect is to raise the lowest of the upper crossbars, which carries the steel rod to which the bob is attached. Hence, if the length of these pieces is properly adjusted, the amount by which the bob is raised may be made exactly to equal the amount of lowering downwards, and thus, the bob being kept in the same position at every change of temperature, the length *ao* will remain unchanged. In winter, in like manner, if the effects of contraction of the steel bars in one direction is exactly balanced by the effect of contraction of the brass bars in the opposite direction, the length of the pendulum will likewise be preserved.

Let *L* = the required length of the pendulum.

*L*₁, *L*₂ = the required length of the steel and brass bars respectively.
*a*₁, *a*₂ = their coefficients of expansion. [spectrum].

Then *L* = *L*₁ + *L*₂ (1), and the

expansion downwards of *L*₁ for any rise of temperature = *L*₁ *a*₁ *t*
 ,, upwards of *L*₂ ,, ,, ,, = *L*₂ *a*₂ *t*,
 but we must have *L*₁ *a*₁ *t* = *L*₂ *a*₂ *t* or *L*₁ *a*₁ = *L*₂ *a*₂ . . . (2).

From the two equations *L* = *L*₁ + *L*₂ . . . (1)

$$L_1 a_1 = L_2 a_2 \quad \dots (2)$$

follows *a*₁ *L* - *a*₁ *L*₁ = - *a*₁ *L*₂ (multiplying by *a*₁)

$$L_1 a_1 = a_2 L_2$$

adding *a*₁ *L* = *L*₂ *a*₂ - *a*₁ *L*₂ = *L*₂ (*a*₂ - *a*₁) or *L*₂ = *L* $\frac{a_1}{a_2 - a_1}$,

multiplying (1) by *a*₂ we have

$$L a_2 = L_1 a_2 + L_2 a_2$$

$$L_1 a_1 = L_2 a_2$$

$$\text{adding } L a_2 + L_1 a_1 = L_1 a_2$$

$$L a_2 = L_1 (a_2 - a_1) \text{ or } L_1 = L \frac{a_2}{a_2 - a_1}$$

For steel and brass $\frac{a_1}{a_2} = \frac{12395}{18555} = \frac{2}{3}$ nearly

∴ *L*₂ = length of brass = *L* . 2

*L*₁ = length of steel = *L* . 3.

224. **Graham's mercurial compensating pendulum.**—This pendulum consists of an iron rod carrying at its lower end a frame in which are fixed one or two glass cylinders containing mercury. When the temperature rises, the lengthening of the rod lowers the centre of gravity and centre of oscillation of the whole; but the expansion of the mercury raises on the other hand both the centre of gravity and centre of oscillation, and thus produces the contrary effect. It follows that the quantity of mercury in the cylinder must be such as to produce an approximately perfect compensation.

If the length of the pendulum beating seconds exactly be L , the height of the mercury in the cylinder may be expressed as a fraction of L , in order that, under the simultaneous expansion by heat of the glass rod and the mercury, the point of oscillation may remain at the same distance from the point of suspension. For, let a be the coefficient of expansion of the substance of the rod which carries the frame, a_1 the coefficient of apparent expansion of mercury, and x the height of the mercury in the vessel.

Then $L \cdot a$ is the quantity by which the centre of oscillation is lowered if the temperature rises one degree; similarly, if we assume the centre of oscillation to be approximately at the middle of the mercurial cylinder in the vessel, this point will be raised upwards through $a_1 \cdot \frac{x}{2}$ for a rise of one degree of temperature. Hence, for perfect compensation,

$$a \cdot L = a_1 \cdot \frac{x}{2}$$

$$\therefore x = \frac{2a}{a_1} L.$$

It must be observed, however, that in cases of adjustment of this kind actual experimental trial is generally preferable to a mere calculation, which in general only approximately indicates the correct quantities to be used.

225. **The compensation-balance.**—In watches and chronometers, where no pendulum is used for regulating the movement, another mode of applying the same principle, viz. the unequal expansion of metals, is employed. *Fig. 84* will serve to give an illustration of it. The inner part of the rim of the balance consists of a lamina of steel attached to brass while the latter is in a state of fusion. Thus neither solder nor pins are required for fixing the two laminæ of steel and brass together; either of these would interfere with the correct and equable ex-

pansion and contraction of the two metals during changes of temperature. This compound rim is cut through in three places, A, B, C, which sets one end of each third part at liberty to move inwards when the temperature is increased, or outwards when it is diminished, since brass expands at a greater rate when heated through the same range of temperature than steel does under the same conditions. D, E, F, are three equal weights, which admit of being fixed by screws upon any part of the compound circular bars. G, H, I, are three heavy-headed screws, which serve as weights to adjust the centre of gravity of the balance to its axis of

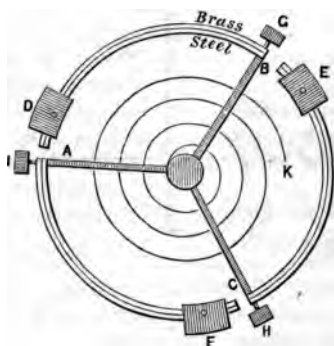


Fig. 84.

vibration, and likewise to adjust its mean rate of motion. When an increase of temperature tends to lengthen the arms of the balance, and to relax the force of its spring K, this would make it go slower; but the same cause, by expanding the brass more than the steel, must bend in the bars, so as to throw the weights D, E, F, nearer the axis, and diminish the effect of the inertia of the balance, which, if the compensation is properly adjusted, will be as speedily carried through its course as before. The contrary compensation takes place with a fall of temperature. The exact adjustment of the weights is found by repeated trials of the going of the machine: if it gain by heat, the weights do more than compensate, and must be moved farther from the extreme ends of the compound bars; but if the gain be produced by cold the weights must be set farther out towards the ends.

Common cylinder watches possess a natural compensation caused by the oil of the cylinder. In warm weather the oil will be more fluid, consequently there will be a quicker action in the escapement; in cold weather the oil will thicken, producing thereby a more sluggish motion, and as a matter of course counteracting in this way the effect of a shortening or contraction of the pendulum-spring.

The behaviour of compound bars under changes of temperature has also been employed for pendulums. Every bar, composed of two laminæ of different metals, differing appreciably in

their rate of expansion by heat, will bend so as to form a convexity on the side of the more expansible metal, when the temperature rises; on the other hand, the bar will bend the opposite

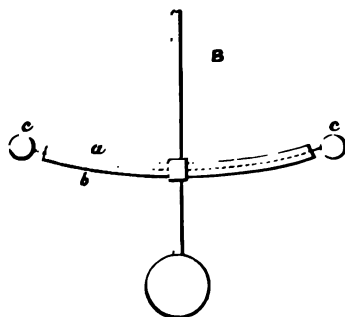
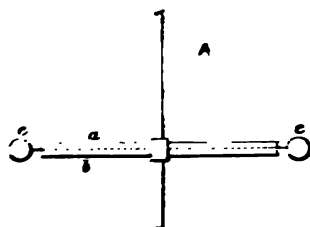


Fig. 85.

way, forming a convexity on the side of less expansible metal, when the temperature falls. Hence, if near the end of a pendulum, as shown in *fig. 85*, such a compound bar be attached, the less expansible metal *a* being uppermost, and carrying at the ends two small weights, *c c*, compensation for temperature will be obtained by careful adjustment of details. If the temperature rises, *b* expands more than *a*, or the form *A* of the pendulum becomes *B*, the small weights *c c* are raised, and the elongation of the pendulum by heating is thus counteracted. If the temperature falls, the opposite effect takes place, the weights *c c* are lowered, while the pendulum rod is shortened.

226. The barometer correction. — It was already pointed out, in the treatise on HYDROSTATICS in this series

(Art. 104, p. 135), that in measuring the pressure of the atmosphere by means of the barometer, and even supposing all necessary provisions be made to indicate the exact height of the columns sustained, two barometers, equally well constructed, would still differ in their indications if they are exposed to different temperatures; for mercury, as has been shown in Arts. 65 to 68, is subject to a definite change of density with every change of temperature. If, therefore, two barometers, equally well constructed, be used in different and distant places, where they are exposed to different temperatures, the same pressure of the atmosphere will sustain mercurial columns of different heights, that which is exposed to the higher temperature being

longer than that which is exposed to the lower. In comparing, therefore, the indications of barometers in different places, it is necessary to observe the temperature, and to 'reduce' the actual height of the barometer observed at that temperature to some standard temperature, usually that of the freezing point of water, in order to render barometric observations made in different places comparable.

The following few problems will make the nature of this reduction, usually called the *temperature correction*, somewhat clearer.

1. The specific gravity of mercury at 0° is 13.59; what is its specific gravity at any other temperature t° ?

Let x = the required specific gravity. The unit volume of mercury being = 1 at 0° , it becomes at $t^{\circ} = 1 + \frac{t}{5550}$ ($\frac{1}{5550}$ being the coefficient of absolute expansion of mercury for 1° C.). Hence, since the specific gravity is proportional to the density of the substance, and the density is inversely proportional to the volumes occupied by the same masses, we have :

$$13.59 : x :: 1 + \frac{t}{5550} : 1$$

$$x = \frac{13.59}{1 + \frac{t}{5550}}$$

2. At the temperature of t° C. the height of the mercurial column of a barometer was observed to = H . What will be its height at 0° C, and what corrections must therefore be applied to the observed height to reduce this to the normal temperature of 0° C.?

If the length of the column at 0° C is = x , then at t°

$$H = x \left(1 + \frac{t}{5550} \right)$$

$$\therefore x = \frac{H}{1 + \frac{t}{5550}} = H - \frac{H \cdot t}{5550} + \dots$$

which gives the correction to be applied = $-\frac{H \cdot t}{5550}$ with sufficient accuracy. For temperatures below 0° t is negative, and the correction becomes then + $\frac{H \cdot t}{5550}$. It should be observed, that for temperature-degrees on Fahrenheit's scale the correction is

$$\pm \frac{H \cdot t'}{9990}$$

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depending as the observed temperature is above or below 32° respectively. * denoting in this case the difference between the observed reading and 32 .

In the case of accurate barometric observations it is necessary, in addition to the correction for the expansion of the mercury by heat, to apply a similar one on account of the metallic scale, especially when, as we shall suppose in the present case, the divisions have been made on a moveable strip of metal which extends from the lower to the upper end of the mercurial column. If t' was the observed temperature of the scale at the time when its subdivision was effected (that temperature being usually stated on the scale itself), and L the height of the barometric column observed at the temperature t' , and reduced to t , then if a' is the coefficient of linear expansion of the substance of the scale, the height L corrected also for expansion of the scale will obviously be,

$$x = L (1 + a' (t' - t))$$

and the correction, therefore,

$$= L a' (t' - t)$$

which value is to be added to the height of the column.

The following table will supply this correction readily calculated for the range of pressure and temperature usual in this country. It is that adopted by the Royal Society, and gives the temperature corrections in decimals of an inch for every degree from 20° to 90° F., and for every half-inch of pressure from $27\cdot0$ to $30\cdot5$ inches. The scale is supposed to be brass, extending from the cistern to the top of the column, the difference between the expansion of brass and mercury being allowed for in the table. The standard temperature of the English unit of measurement is 62° F. and not 32° ; hence, in consequence of the difference of expansion of scale and mercurial column, there is a certain temperature where no correction is required: this is in this case $28^{\circ}\cdot5$. The table may, of course, be used also for temperatures lower than $28^{\circ}\cdot5$, by noting how many degrees the given temperature is below $28^{\circ}\cdot5$, and then looking at the temperature which is just as far above $28^{\circ}\cdot5$, the correction will be found, but it must be added instead of being subtracted. Thus, suppose we wish to find the temperature correction at 50° , the height of the barometer being 30 inches. Looking for the correction at $3^{\circ}\cdot5$, which is as far above $28^{\circ}\cdot5$ as 20° is below $28^{\circ}\cdot5$, we find it to be $\cdot023$; hence $\cdot023$ must be added to the observed reading, instead of being subtracted.

Table for Reducing Barometric Observations to the Freezing-Point (32° F)

Temp. Fah.	English Inches.								Temp. Fah.
°	27	27.5	28	28.5	29	29.5	30	30.5	°
29	.001	.001	.001	.001	.001	.001	.001	.001	29
30	.004	.004	.004	.004	.004	.004	.004	.004	30
31	.006	.006	.006	.006	.007	.007	.007	.007	31
32	.008	.009	.009	.009	.009	.009	.009	.010	32
33	.011	.011	.011	.012	.012	.012	.012	.012	33
34	.013	.014	.014	.014	.014	.015	.015	.015	34
35	.016	.016	.016	.017	.017	.017	.018	.018	35
36	.018	.019	.019	.019	.020	.020	.020	.021	36
37	.021	.021	.021	.022	.022	.022	.023	.023	37
38	.023	.023	.024	.024	.025	.025	.026	.026	38
39	.025	.026	.026	.027	.027	.028	.028	.029	39
40	.028	.028	.029	.029	.030	.030	.031	.031	40
41	.030	.031	.031	.032	.033	.033	.034	.034	41
42	.033	.033	.034	.034	.035	.036	.036	.037	42
43	.035	.036	.036	.037	.038	.038	.039	.040	43
44	.037	.038	.039	.040	.040	.041	.042	.042	44
45	.040	.041	.041	.042	.043	.044	.044	.045	45
46	.042	.043	.044	.045	.045	.046	.047	.048	46
47	.045	.046	.046	.047	.048	.049	.050	.051	47
48	.047	.048	.049	.050	.051	.052	.052	.053	48
49	.050	.050	.051	.052	.053	.054	.055	.056	49
50	.052	.053	.054	.055	.056	.057	.058	.059	50
51	.054	.055	.056	.057	.058	.059	.060	.061	51
52	.057	.058	.059	.060	.061	.062	.063	.064	52
53	.059	.060	.061	.063	.064	.065	.066	.067	53
54	.062	.063	.064	.065	.066	.067	.068	.070	54
55	.064	.065	.066	.068	.069	.071	.061	.072	55
56	.066	.068	.069	.070	.071	.073	.074	.075	56
57	.069	.070	.071	.073	.074	.075	.076	.078	57
58	.071	.073	.074	.075	.077	.078	.079	.081	58
59	.074	.075	.076	.078	.079	.080	.082	.083	59
60	.076	.077	.079	.080	.082	.083	.085	.086	60
61	.078	.080	.081	.083	.084	.086	.087	.089	61
62	.081	.082	.084	.085	.087	.088	.090	.091	62
63	.083	.085	.086	.088	.089	.091	.093	.094	63
64	.086	.087	.089	.090	.092	.094	.095	.097	64
65	.088	.090	.091	.093	.095	.096	.098	.100	65
66	.090	.092	.094	.096	.097	.099	.101	.102	66
67	.093	.095	.096	.098	.100	.102	.103	.105	67
68	.095	.097	.099	.101	.102	.104	.106	.108	68
69	.098	.100	.101	.103	.105	.107	.109	.110	69

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Table for Reducing Barometric Observations to the Freezing-Point (32° F.)—(continued).

Temp. Fah.	English Inches.								Temp. Fah.
°	27	27·5	28	28·5	29	29·5	30	30·5	°
70	·100	·102	·104	·106	·108	·109	·111	·113	70
71	·102	·104	·106	·108	·110	·112	·114	·116	71
72	·105	·107	·109	·111	·113	·115	·117	·119	72
73	·107	·109	·111	·113	·115	·117	·119	·121	73
74	·110	·112	·114	·116	·118	·120	·122	·124	74
75	·112	·114	·116	·118	·120	·122	·125	·127	75
76	·114	·117	·119	·121	·123	·125	·127	·129	76
77	·117	·119	·121	·123	·126	·128	·130	·132	77
78	·119	·122	·124	·126	·128	·130	·133	·135	78
79	·122	·124	·126	·128	·131	·133	·135	·137	79
80	·124	·126	·129	·131	·133	·136	·138	·140	80
81	·126	·129	·131	·134	·136	·138	·141	·143	81
82	·129	·131	·134	·136	·138	·141	·143	·146	82
83	·131	·134	·136	·139	·141	·143	·146	·148	83
84	·134	·136	·139	·141	·144	·146	·149	·151	84
85	·136	·139	·141	·144	·146	·149	·151	·154	85
86	·138	·141	·144	·146	·149	·151	·154	·156	86
87	·141	·143	·146	·149	·151	·154	·157	·159	87
88	·143	·146	·149	·151	·154	·157	·159	·162	88
89	·146	·148	·151	·154	·156	·159	·162	·165	89
90	·148	·151	·153	·156	·159	·162	·164	·167	90

The following example, calculated independently, will show the accuracy of the tabular correction. An English barometer with a brass scale, correctly graduated, reads 30 inches at 45° F. What is the pressure in true inches of mercury, reduced to the specific gravity the mercury has at 32° F. ?

Since the scale is only correct at 62°, the scale has contracted for a fall of temperature through 17°, and shows therefore a higher reading than it would show if the scale could be made to expand suddenly through the 17° its temperature has fallen. Taking 0·00001 as coefficient of linear expansion of brass for 1° F., the true length of the mercurial column at its present temperature of 45° is found from the proportion :—

$$30 : x :: 1 + 0·00001 \times 17 : 1$$

$$\text{or} \quad x = \frac{30}{1·00017} = 29·995$$

But 29·995 inches of mercury at 45° will contract in falling to 32° F., and since $\frac{1}{8800}$ is the coefficient of expansion of mercury

for 1° F., we have for the true length = H , of the mercurial column at 32° , the proportion :—

$$29.995 : H :: 1 + \frac{13}{9990} : 1$$

$$\therefore H = 29.956 \text{ inches.}$$

Looking into the above table under 30 inches pressure, and 45° temperature, we find the correction to be $-.044$, which gives

$$H = 30 - .044 = 29.956 \text{ inches,}$$

the same as found by calculation.

The following example will serve to illustrate the same principle, if different units of length and centigrade degrees are used.

A barometer with a brass scale, which has been adjusted at 0° C., stands at 778 millimetres when the temperature is 20° C. What pressure in kilogrammes per square centimetre does this indicate? Given are the following data :

Coefficient of linear expansion of brass = 0.000188 .

Coefficient of cubical expansion of mercury = 0.0001803 .

Weight of 1 centimetre of mercury at 0° C. = 13.596 grammes.

The scale being only correct at 0° , it would contract and therefore indicate a *greater* length of the mercurial column, if it could assume its correct dimension by a sudden fall of temperature from 20° to 0° . The true length, x , of the mercurial height is found from the proportion

$$1 + 0.000188 \times 20 : 1 :: x : 778$$

$$x = 778 (1 + 0.000188 \times 20) = 778.3 \text{ millimetres.}$$

But the weight of one cubic centimetre of mercury at 0° being 13.596 , the weight of a cubic centimetre at 20° is

$$\frac{13.596}{1 + 20 \times 0.0001803} = 13.547 \text{ grammes.}$$

We have therefore a column of 778.3 millimetres, or 77.83 centimetres, and if the column have a section of one square centimetre, its weight is obviously

$$77.83 \times 13.547 \text{ grammes} = 1054.363 \text{ grammes.}$$

227. Superficial and cubical expansion.—It has been shown in Art. 48, page 41, that we may use as coefficient of superficial expansion twice the coefficient of linear expansion, and similarly as coefficient of cubical expansion of a solid we may use three times that of linear expansion. The following

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problems will illustrate the practical use of the coefficients of superficial and cubical expansion :—

1. A square plate of iron has each side 3 metres long at 0° C. What is the superficial area of the plate at 64° C., the coefficient of linear expansion of iron being 0.0000122 ?

Here we may proceed thus :

The side at 0° being 3 metres, at 64° it will be

$$3 (1 + 0.0000122 \times 64) = 3.0022424 \text{ metres ;}$$

hence the area at 64° will be

$$(3.0022424)^2 = 9.0135 \text{ square metres.}$$

Or, by employing the principle that the coefficient of superficial is twice that of linear expansion, we have

$$\begin{aligned} \text{Area at } 64^{\circ} &= 9 (1 + 2 \times 64 \times 0.0000122) \\ &= 9.0132 \text{ square metres,} \end{aligned}$$

a result which differs only by a very small quantity, which is practically insensible, from the preceding one, and is obtained with considerably less trouble.

2. Two bars, one of copper and the other of platinum, have the shape of rectangular prisms, and are of exactly equal dimensions at 0° C., their length being at that temperature 1.25 metre. What will be the difference in their lengths when heated to 100° ; and what will be the ratio of their sections at that temperature, if the coefficient of linear dilatation of copper is $\frac{1}{53,500}$, and that of platinum $\frac{1}{116,000}$?

1st. The bar of copper has at 100° a length of

$$1.25 \left(1 + \frac{100}{53,500} \right),$$

and the bar of platinum of

$$1.25 \left(1 + \frac{100}{116,000} \right);$$

hence the difference in their lengths is clearly

$$1.25 \left(\frac{1}{535} - \frac{1}{1161} \right) = 0.00124 \text{ metre.}$$

2nd. If we denote the two adjacent sides of the rectangle which forms the section of each bar at 0° , by a and b , the area of the section of the copper bar is at 100° :—

$$ab \left(1 + \frac{100}{53,500} \right)^2,$$

and that of the platinum bar at 100° :—

$$ab \left(1 + \frac{100}{116,000} \right)^2;$$

and the ratio of these two quantities is

$$\frac{536^2}{1162^2} \times \frac{1161^2}{535^2} = 1.00201.$$

3. A block of sandstone has at -10°C. a volume of 12 cubic feet. By how much will its volume increase if it be heated to 40° , the coefficient of linear expansion being $\frac{1}{88200}$?

$$\begin{aligned} \text{Increase} &= 12 \times 50 \times 3 \times \frac{1}{85,200} = \frac{3}{142} \text{ cubic feet,} \\ &\text{or } 36\frac{1}{2} \text{ cubic inches.} \end{aligned}$$

4. A glass vessel contains at 0° one litre of water. What is the internal capacity of the vessel, if filled with water at 90°C. , the coefficient of linear expansion of glass being 0.000009 ?

$$\begin{aligned} \text{Capacity at } 90^\circ &= 1 + 3 \times 0.000009 \times 80 \\ &= 1.00216 \text{ litre.} \end{aligned}$$

5. According to Hallström (compare Arts. 70 and 72, pages 66 or 68), a volume of water = V at 0° becomes at a temperature of t° :—

$$V_1 = V (1 - .000057577 t + .0000075601 t^2 - .000000035091 t^3)$$

when t lies between 0° and 30°C. , and

$$V_1 = V (1 - .000094178 t + .0000053366 t^2 - .000000010409 t^3)$$

when t is between 30° and 100° . Find from this the volume of a quantity at $8^\circ.9$, $11^\circ.5$, and 50° respectively, the volume at 0° being unity.

Placing the three temperatures respectively in the above equation, we find :—

$$(i) \text{ Volume at } 8^\circ.9 = 1, \text{ that is the volume is the same at } 8^\circ.9 \text{ as at } 0^\circ.$$

$$(ii) \quad ,, \quad 11^\circ.5 = 1.0003$$

$$(iii) \quad ,, \quad 50^\circ = 1.00733.$$

6. A glass tube, closed at one end, was drawn out at the other to a capillary point. It was weighed, then filled with water and weighed again, and the weight of the water at 0°C. was found to be 124 grammes. By heating the apparatus up to 100°C. , 6 grammes of water were driven out. Assuming the coefficient of cubical expansion of glass to be $.000026$, find the expansion of water between 0° and 100°C.

Let x be the total expansion of a unit volume between 0° and 100° , then taking the weight in grammes to represent the volume in cubic centimetres, a volume of 124 at 0° will at 100° become :

$$124 (1 + x);$$

but the vessel will also expand, and its capacity will become at 100° :

$$124 (1 + 0.000026 \times 100);$$

and the quantity expelled, which is

$$6(1+x),$$

will clearly represent the difference between the expanded water and the expanded vessel; hence we have the equation :

$$124(1+x) - 124(1 + .000026 \times 100) = 6(1+x);$$

or, x = the expansion of the unit volume between 0° and 100°
 = $\cdot 05358$, or a little more than $\frac{1}{20}$ of the unit volume at 0° .

228. **Illustrations of methods of determining coefficients of expansion.**—The preceding problem is an illustration of a method of finding the rate of expansion of a liquid if that of the vessel is known. Some of the following problems will further illustrate the methods for determining the coefficients of cubical expansion of substances, explained in Chapters III., IV., and V.

1. A glass bottle, having the shape of the weight thermometer shown in *fig. 22*, page 38, holds at 0°C. 10169.3 grains of mercury. It is then heated to 100°C. , at which temperature it is found to retain only 10011.4 grains. Knowing that the mean coefficient of cubical dilatation of mercury between 0° and 100° is $= 0.00018153$ for each degree centigrade, find the mean coefficient of cubical dilatation of the glass bottle for the same range of temperature.

We have first to find the weight of the mercury which should have occupied the same volume—that is, the interior of the glass bottle, if the latter had not expanded. We have the proportion :—

Weight of mercury occupying a given volume at 100° : weight of mercury occupying the same volume at 0° :: 1 : 1.018153; or,

$$\left. \begin{array}{l} \text{Weight of mercury occupying} \\ \text{the given volume at } 100^{\circ} \end{array} \right\} : 10169.3 :: 1 : 1.018153.$$

$$= \frac{10169.3}{1.018153} = 9987.9$$

It follows that only 9987.9 grains should have remained in the bottle, if the bottle had not expanded. In consequence of its own expansion the bottle holds thus $10011.4 - 9987.9 = 23.5$ grains more at 100° than it would have held if it could have been maintained at 0° . Hence

$$\left. \begin{array}{l} \text{Volume of bottle} \\ \text{at } 0^{\circ} \end{array} \right\} : \left. \begin{array}{l} \text{Volume of bottle} \\ \text{at } 100^{\circ} \end{array} \right\} :: 9987.9 : 10011.4$$

$$:: 1 : 1.000235.$$

The total expansion of the unit volume is therefore between 0° and $100^\circ = \cdot 00235$, and hence the mean coefficient of the cubical expansion of the bottle between 0° and $100^\circ = \cdot 0000235$.

2. Let the bottle used in the preceding experiment contain a piece of iron weighing 2000 grains, and the remaining space filled at 0° with mercury, the weight of the mercury being 6707·8 grains. The bottle is then heated to 100° , and 108·4 grains of mercury run out. Find from this the cubical expansion of the iron for the range of temperature from 0° to 100° .

Had there been no expansion of iron or bottle, the 6707·8 grains of mercury would have alone expanded in proportion of $1 : 1\cdot 011153$, or the weight required to fill the bottle would

have been $\frac{6707\cdot 8}{1\cdot 018153} = 6588\cdot 2$.

Hence $6707\cdot 8 - 6588\cdot 2 = 119\cdot 6$ grains would have run out.

Again, the expansion of the bottle, as determined by the previous problem, enables it to contain 23·5 grains more at 100° . Hence if the iron had not expanded, but only the bottle, $119\cdot 6 - 23\cdot 5 = 96\cdot 1$ grains ought to have run out.

But the actual loss was $6707\cdot 8 + 6588\cdot 2 = 108\cdot 4$, and $108\cdot 4 - 96\cdot 1 = 12\cdot 3$ must have been pushed out by the expansion of the iron.

Hence a piece of iron weighing 2000 grains at 0° will expand when heated to 100° by a space which is occupied by 12·3 grains of mercury at 100° .

Now the specific gravities of mercury and iron at that temperature being taken as 13·2 and 7·8,

$$13\cdot 2 : 7\cdot 8 :: 12\cdot 3 : x = 7\cdot 26 \text{ grains,}$$

if the space were filled by iron, and there appears that the remaining 1992·74 grains fill the same space as that occupied by the original 2000 grains at 32° . Therefore $\frac{7\cdot 26}{1992\cdot 74} = \cdot 00364$ is the cubical expansion.

3. Several observers (Deluc, Despretz, Kopp, Pierre) used for experimental determination of the rates of expansion of liquids so-called *Dilatometers*. To find a formula for calculating the expansion, we have the following data :—

The liquid under experiment is contained in a kind of thermometer with large bulb, and divided stem. By mercury weighings the cubical contents of the bulb up to the zero of the scale is known, and the volume of 1 part of the division at 0° (the former v_o , the latter v_c); then the *true* volume of the liquid which reaches to n_o divisions at 0° is

$$W_o = v_o + n_o v_c.$$

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Heated to t° , the liquid rises n divisions, and if w is the increase in volume,

$$w_0 + w = (v_0 + n v_0) (1 + a t),$$

a being the coefficient of cubical expansion of the vessel. From these two equations

$$w = (n - n_0) v_0 + a v_0 t$$

if the small product $v_0 a$ be neglected.

In this equation the first term on the left side represents the apparent expansion, the second term gives the expansion of the vessel.

4. A body of known weight is successively weighed in the same liquid at different temperatures. The rate of expansion of the body being known, find the rate of expansion of the liquid.

Let v_0 = volume of body at 0° ,

a = coefficient of expansion of body,

P_0, P , loss of weight of body in the liquid at 0° and t ,

s_0, s , specific gravity of liquid at 0° and t .

Then $s_0 = \frac{P_0}{v_0}$, that is, the weight divided by the volume, gives

the specific gravity. Similarly,

$$s = \frac{P}{v_0 (1 + a t)} \cdot \frac{s_0}{P_0} = \frac{P}{P_0 (1 + a t)}$$

and if $v_0, v_0 + w$ the corresponding volumes,

$$\frac{v_0 + w}{v_0} = \frac{s_0}{s} = \frac{P_0 (1 + a t)}{P}$$

$$\therefore \frac{w}{v_0} = \frac{P_0}{P} (1 + a t) - 1.$$

5. A spherical vessel, of which the internal diameter is $1\frac{1}{2}$ metre, is made of a material which has a coefficient of expansion (linear) of $\frac{1}{25000}$. How much mercury will this vessel contain at 25°C . ?

The volume of the vessel at 0° is

$$v = \frac{4}{3} \pi r^3 = \frac{4 \times 3 \cdot 1416 \times 8}{3 \times 27} = 1 \cdot 24114144 \text{ cubic metres.}$$

But from the formula $P = v \cdot D$, or the weight is equal to the product of the volume into the specific gravity, we must multiply this number by $13 \cdot 6$, the specific gravity of mercury at 0° , in order to find the weight of mercury in the vessel at 0° . To understand our result, we must, however, bear in mind that,

1 cubic centimetre of water weighs at 4° 1 gramme,

\therefore 1 " " " mercury " at 0° $13 \cdot 6$ grammes,

and 1 cubic metre = 1,000,000 cubic centimetres.

∴ 1 cubic metre of water weighs 1,000,000 grammes
= 1,000 kilogrammes,

and 1 cubic centimetre of mercury weighs 13,600 kilogrammes.

Multiplying now the volume in cubic metres, we find the weight to be $1.24414144 \times 13600 = 16879.5$ kilogrammes. But if

v = volume of vessel at 0° ,

and $v' = \quad , \quad , \quad , \quad$ at 25° ,

then $v' = v \left(1 + \frac{3}{2500} \times 25 \right) = v(1.03)$,

and the density of mercury at 25° will be

$$\frac{13.6}{1 + \frac{1}{5550} \cdot 25} = \frac{13.6 \times 222}{223};$$

hence, if 16879.8 kilogrammes is the weight of the mercury filling the vessel at 0° , the weight filling the same space at 25°

will be $\frac{16879.5 \times 222}{223};$

but the original space is now $v(1.03)$, therefore the required weight is:—

$$16879.5 \times \frac{222}{223} \times 1.03 = 17307.9 \text{ kilogrammes.}$$

6. A vessel A is filled at t° with a liquid of which the coefficient of absolute expansion is known to be β . The weight of the liquid at t° is found to be w . It is then heated to t'° , and at that temperature contains only a weight of the liquid = w' . Find from this the coefficient of cubical expansion of the solid substance of the vessel used, = α . (Dulong's method.)

Let s_0 be the specific gravity of the liquid used at 0° . Then its specific gravity at t° and t'° respectively will be

$$s = \frac{s_0}{1 + \beta t'}, \quad s' = \frac{s_0}{1 + \beta t'}$$

the volume at t will also be $= \frac{w}{s}$, and at $t' = \frac{w'}{s'}$. Further, if the volumes at 0° , at t° , and at t'° be denoted by v_0 , v , v' respectively, we have:—

$$v_0 = \frac{v}{1 + \alpha t} = \frac{v'}{1 + \alpha t'},$$

or

$$\begin{aligned} v + v \alpha t' &= v + v' \alpha t \\ v - v' &= \alpha (v' t - v t'), \end{aligned}$$

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$$\text{or} \quad \alpha = \frac{v - v'}{v' t - v t'} = \frac{\frac{w}{s} - \frac{w'}{s'}}{\frac{w' t - w t'}{s' s}} = \frac{w s' - w' s}{w' s t - w s' t'}$$

$$\text{or} \quad \alpha = \frac{\frac{w.s_0}{1 + \beta t'} - \frac{w'.s_0}{1 + \beta t}}{\frac{w'.s_0 t}{1 - \beta t} - \frac{w.s_0 t'}{1 + \beta t'}} = \frac{w(1 + \beta t) - w'(1 + \beta t')}{w'(1 + \beta t)t - w(1 + \beta t')t'}$$

If we experiment at 0° , then $t' = 0$, and the expansion becomes

$$\frac{1}{t} \left(\frac{w}{w'} (1 + \beta t) - 1 \right).$$

7. The specific gravity of mercury at 0° is 13.59. What is the volume of 40 kilogrammes of the metal at 100° C. ?

From $P = v D$ (see problem 5 in this article) we have :—

$$v = \frac{40}{13.59} = 2.94 \text{ litres at } 0^\circ,$$

and at 100° :

$$v' = v (1 + \alpha t) = 2.94 \left(1 + \frac{100}{5550} \right) = 2.99 \text{ litres.}$$

8. A glass globe, at 0° and 760 millimetres pressure, is heated to 100° , and 1 gramme of gas escapes. What was the volume of the glass vessel, and the weight of the enclosed gas ?

Weight of 1 litre at 0° and 760 millimetres pressure = 1.293 gramme. Coefficient of cubical dilatation of glass = $\frac{1}{38700}$;

Let v = volume of globe at 0° , $\therefore v \left(1 + \frac{100}{38700} \right)$ is the volume at 100° .

The volume of 1 litre of air at 100° is, on the other hand, $1 + 100 \times .003665$, and its weight = $\frac{1.293}{1 + 100 \times .003665}$ gramme,

\therefore the weight of the air contained at 100° in the globe is

$$v \left(1 + \frac{100}{38700} \right) \frac{1.293}{1.367} = v \times .947.$$

Now at 0° the volume weighs $v \times 1.293$, and by the result of the experiment,

$$v (1.293 - .947) = 1 \text{ gramme} \\ \therefore v = 2.9 \text{ litres.}$$

The weight of the gas $\therefore 2.9 \times 1.293 = 2.749$ grammes.

9. A vase in the shape of a cone, 0·87 metre high and having a base of 0·23 metre radius, is filled with mercury at the temperature of 26° C. Find the weight of the mercury, its density at 0° being 13·596, and its coefficient of cubical dilatation 0·00018.

$$\text{Volume} = \frac{1}{3} \pi r^2 h = \frac{1}{3} \pi (2\cdot3) \times 8\cdot7 = 48\cdot186 \text{ cubic decimetres.}$$

$$\text{Density} = \frac{D'}{1 + \kappa t} = \frac{13\cdot596}{1 + 0\cdot00018 \times 26} = 13\cdot533.$$

$$\text{Weight} = 13\cdot533 \times 48\cdot186 = 652\cdot101 \text{ kilogrammes.}$$

10. A vessel of glass encloses at 0° a piece of iron, and the remaining space is filled up with mercury. The weight of the iron is 100 grammes ; the weight of the mercury 120 grammes. The vessel is heated, and the following data being given, what is the weight of the mercury which flows out ?

Specific gravity of iron at 0° = 7·78 ; coefficient of cubical expansion of iron = $\frac{1}{28,700}$.

Specific gravity of mercury at 0° = 13·59 ; coefficient of cubical expansion of mercury = $\frac{1}{5550}$.

$$\text{Coefficient of expansion of glass vessel} = \frac{1}{38,700}.$$

Let v , v' , v'' denote the volumes of the vessel, iron, and mercury at 0° respectively. Then,

$$v = v' + v'' \text{ at } 0^\circ.$$

$$\text{At } 100^\circ v \text{ becomes } v \left(1 + \frac{100}{38,700} \right) \dots (i.)$$

$$v' \quad ,, \quad v' \left(1 + \frac{100}{28,700} \right) \dots (ii.)$$

$$v'' \quad ,, \quad v'' \left(1 + \frac{100}{5,550} \right) \dots (iii.)$$

The volume, x , of the mercury which flows out is clearly equal to the difference between the volume of the vessel at 100°, and the sum of the volumes of the iron and mercury at the same temperature, that is :—

$$x = (ii.) + (iii.) - (i.)$$

$$= v' \left(1 + \frac{100}{28,700} \right) + v'' \left(1 + \frac{100}{5,550} \right) - v \left(1 + \frac{100}{38,700} \right).$$

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Replacing in this equation v by $v' + v''$, and reducing, we shall

have $x = \frac{v'}{287} + \frac{10 v''}{555} - \frac{v' - v''}{387}$. But the formula $P = v D$ gives

$$v' = \frac{100}{7.78}, \quad v'' = \frac{120}{13.59},$$

substituting these values in the above equation, we obtain :—

$$x = \frac{100}{287 \times 7.78} + \frac{1200}{555 \times 13.59} - \frac{1}{387} \left(\frac{100}{7.78} + \frac{120}{13.59} \right) = 0.147856$$

cubic centimetres. In order to obtain the *weight* of the mercury we must now multiply x by the specific gravity of mercury at 100° , or by

$$\frac{13.59}{1 + 100} = \frac{13.59 \times 111}{5550}$$

$$\therefore \text{weight} = \frac{0.147856 \times 13.59 \times 111}{113} = 1.974 \text{ grammes.}$$

11. A sphere of copper, of which the radius at $0^\circ = 0.2651$ metre, is placed into a vessel containing a liquid of unknown temperature, and the radius is found to have increased to 0.2657 metre. Find the temperature of the liquid, if the coefficient of cubical expansion of the copper = $\frac{1}{19,400}$.

Let a = the radius at 0° ,

a' = „ at the required temperature x° .

Then the volume at 0° will be

$$v = \frac{4}{3} \pi a^3,$$

and at x°

$$\begin{aligned} v' &= \frac{4}{3} \pi a'^3 = v (1 + a x) \\ \therefore \frac{4}{3} \pi a'^3 (1 + a x) &= \frac{4}{3} \pi a^3 \\ a^3 + a^3 a x &= a'^3 \\ x &= \frac{a'^3 - a^3}{a^3 a}. \end{aligned}$$

Substituting the given numerical values we find

$$x = 132^\circ.03.$$

By taking the third part of the cubical coefficient as linear coefficient, and considering that the total expansion must be equal to the original length of the radius multiplied by the

increase of temperature and by the coefficient of linear expansion, the calculation may be considerably shortened, thus :

$$0.2657 - 0.2651 = x \times 0.2651 \times \frac{1}{3 \times 19,400},$$

or

$$x = 131^{\circ}.72,$$

which gives very approximately the same result.

12. A cone of copper has a height 0.25 metre, and its base has a radius of 0.15 metre at 0° . Find the height and radius of the cone if it is heated to 180° C.

The volume of the cone is by geometry $= \pi r^2 \frac{h}{3}$, r being the radius at 0° , and h the height at the same temperature ;

$$\text{or } v_0 = \frac{3.14159 \times (0.15)^2 \times 0.25}{3} = 0.005890481 \text{ cubic metre.}$$

At 180° we shall have the volume $= v_1 = v_0 (1 + a t)$,

$$v_1 = 0.005890481 \left(1 + \frac{180}{19,400} \right),$$

$$v_1 = 0.00594513 \text{ cubic metre.}$$

The cone being similar to its original geometrical figure at all temperatures, we shall have—

$$\begin{aligned} \frac{v_0}{v_1} &= \frac{r^3}{r_1^3} = \frac{h^3}{h_1^3} \\ r_1 &= \sqrt[3]{\frac{v_1 r^3}{v_0}} = 0.150463 \text{ metre} \\ h_1 &= \sqrt[3]{\frac{v_1 h^3}{v_0}} = 0.250771 \text{ metre.} \end{aligned}$$

229. **Expansion of Gases.**—The following formulæ will show how the external pressure, elastic force, volume, and temperature of a gas, are mutually connected.

(a) The volume of a gas 0° is v . How much is it at t° C. ?

$$v' = v (1 + .003665 t^{\circ}) \text{ or } = v \left(1 + \frac{t^{\circ}}{273} \right)$$

(b) At t° the volume is v ; what is it at t_1° , if the pressure remains constant ?

$$\begin{aligned} v : v' :: 1 + .003665 t : 1 + .003665 t_1 \\ v' = \left(v \frac{1 + .003665 t_1}{1 + .003665 t} \right) = v \frac{1 + \frac{t_1}{273}}{1 + \frac{t}{273}} = v \left(\frac{273 + t_1}{273 + t} \right) \end{aligned}$$

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(c) How is the volume altered if the pressure p changes to p_1 ?
 Since

$$v : v' :: p_1 : p,$$

$$\therefore v' = \frac{p}{p_1} v = \frac{p}{p_1} v \left(\frac{273 + t_1}{273 + t} \right);$$

if the temperature has changed at the same time.

(d) In general, if v_1, t_1, p_1, E_1 , express the volume, temperature, external pressure, and elastic force of a gas in one state of combined circumstances, and v_2, t_2, p_2, E_2 , the same elements in another state, and a is the coefficient of expansion of the gas, the relation between these physical elements may be expressed thus :

$$(I) \quad v_1 : v_2 :: 1 + a t_1 : 1 + a t_2.$$

$$(II) \quad v_1 : v_2 :: p_2 : p_1.$$

$$(III) \quad E_1 : E_2 :: p_1 : p_2.$$

From which may be derived the following :

$$(1) \quad \frac{v_1}{v_2} = \frac{1 + a t_1}{1 + a t_2} \therefore v_2 = \frac{1 + a t_2}{1 + a t_1} \cdot v_1$$

$$(2) \quad v_2 = \frac{v_1 \cdot p_1}{p_2} = v_1 \cdot \frac{1 + a t_2}{1 + a t_1} \cdot \frac{p_1}{p_2}$$

$$\frac{v_2}{v_1} = \frac{1 + a t_2}{1 + a t_1} \cdot \frac{p_1}{p_2}$$

$$(3) \text{ Since } \frac{p_1}{p_2} = \frac{E_1}{E_2} \cdot \frac{v_2}{v_1} = \frac{1 + a t_2}{1 + a t_1} \cdot \frac{E_1}{E_2},$$

$$\text{or} \quad \frac{E_2}{E_1} = \frac{v_1}{v_2} \cdot \frac{1 + a t_2}{1 + a t_1}.$$

The following problems will render the application of these formulæ much clearer.

1. The receiver of an air-pump has a capacity of 7.53 litres and is filled with air at 0° and 760 millimetres pressure. After exhausting it partially, the temperature is found to be 15° , and the pressure in the receiver 210 millimetres. Find the weight of the air left in the receiver and the weight removed, if 1 litre of air at 0° and 760 millimetres pressure weighs 1.3 grammes.

1st. Since 1 litre weighs 1.3 gramme, there are at starting $7.53 \times 1.3 = 9.789$ grammes of air in the receiver, at 0° , and 760 millimetres pressure. Supposing that the temperature remained unaltered, the weight of air filling the same space at 210 millimetres pressure is found by considering that the weights are proportional to the pressures, and hence—

$$\frac{9.789}{x} = \frac{760}{210},$$

$$\text{or} \quad x = \frac{9.789 \times 210}{760} = 2.705 \text{ grammes.}$$

2nd. To find the weight of the same volume of air at 15° , which at 0° weighs 2.705 grammes, we have—

$$\frac{2.705}{w} = \frac{1 + \alpha t}{1}, \text{ or weight at } 15^{\circ} = \frac{2.705}{1 + 0.003665 \times 15}.$$

\therefore weight of air left in the receiver = $\frac{2.705}{1.855} = 2.564$ grammes.

Since only 2.564 grammes are thus really left, and the original quantity was 9.789 grammes, the quantity removed is $9.789 - 2.564 = 7.225$ grammes.

2. A litre of gas weighs 1.562 gramme at 0° and 760 millimetres pressure. Find the weight of a litre of the same gas at 25° C., and 780 millimetres pressure.

The volume of 1 litre = v_1 becomes under the new conditions of temperature and pressure,

$$\begin{aligned} v_2 &= v_1 (1 + 0.003665 \times 25) \frac{760}{780} \\ &= \frac{76}{78} \times 1.0915 = 1.063 \text{ litre.} \end{aligned}$$

But 1.063 litre weighing 1.562 grammes, we find the weight of 1 litre from the proportion :

$$1.063 : 1 :: 1.562 : x = 1.46 \text{ gramme.}$$

3. A glass vessel has a capacity of 5 litres, at 0° , and is filled at that temperature and a pressure of 760 millimetres with carbonic acid. The vessel is then heated to 100° , and the pressure falls to 750 millimetres. Find the quantity of gas which has escaped. (The coefficient of dilatation of carbonic acid is 0.00367; its specific gravity, compared with air, is 1.5; one litre of air at 0° and 760 millimetres pressure weighs 1.293 grammes; the coefficient of expansion of the glass vessel is $\frac{1}{38700}$).

At 100° and 750 millimetres the volume of the carbonic acid will be $\frac{5 (1 + 0.00367 \times 100) 76}{75} = 6.926$ litres.

At the same temperature the volume of the glass vessel is

$$5 \left(1 + \frac{100}{38,700} \right) = 5.013 \text{ litres.}$$

The volume of the escaped gas is thus :

$$6.926 - 5.013 = 1.913 \text{ litre.}$$

In order to find the weight of this volume, we know that the original 5 litres of carbonic acid weighed

$$5 \times 1.5 \times 1.293 = 9.697 \text{ grammes ;}$$

and since the gas in its expanded state, at 100° , and 750 millimetres pressure, weighed the same, but measured 6.926 litres, we find the weight of 1.913 litre from the proportion :

$$6.926 : 1.913 :: 9.697 : x = 2.678 \text{ grammes.}$$

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4. A quantity of dry air, which occupies 25 cubic centimetres, at 0° and 760 millimetres pressure, is introduced into an empty glass vessel which has an internal capacity of 250 cubic centimetres at 0° . The vessel being hermetically sealed and heated to 100° , what will be the tension of the enclosed air at that temperature? (Coefficient of expansion of the glass vessel = $\frac{1}{38700}$.)

At 100° the capacity of the vessel will be

$$250 \left(1 + \frac{100}{38700} \right) = \frac{250 \times 388}{387}.$$

At the same temperature the volume of the enclosed air, if the pressure were 760 millimetres, would be

$$25 (1 + .003665 \times 100) = 25 \times 1.3665.$$

But the actual volume at the pressure x is

$$\frac{250 \times 388}{387};$$

and the pressure being inversely as the volumes, we have—

$$\begin{aligned} \frac{x}{25 \times 1.3665} &= \frac{760 \times 387}{250 \times 388} \\ x &= \frac{25 \times 1.3665 \times 760 \times 387}{250 \times 388} = 103.6 \text{ millimetres.} \end{aligned}$$

5. A glass vessel with a narrow neck, which can be closed by a stop-cock and screwed to the plate of an air-pump, is filled with a gas, at the temperature t° and pressure H in millimetres. Show how to find the weight of the enclosed gas at the normal pressure and temperature.

The vessel is first weighed, and then exhausted by the air-pump until the gauge attached to it indicates a pressure of say h millimetres. The vessel is now removed from the pump and again weighed. If w and w' are the two weights found before and after exhausting, then $w - w'$ represents the quantity of gas which would fill the vessel under a pressure of $H - h$, at the temperature t . The same quantity of gas would, under the normal pressure, fill a volume of

$$(w - w') \times \frac{760}{H - h};$$

and if the temperature were reduced from t° to 0° , its density would increase in the ratio $1 : 1 + \frac{t}{273}$. The required weight is therefore :

$$(w - w') \times \frac{760}{H - h} \left(1 + \frac{t}{273} \right).$$

If the expansion of the glass vessel is to be taken into account this expression must be divided by $1 + \frac{t}{38,700}$.

230. Influence of expansion on the specific gravity of bodies.—In determining the specific gravity of bodies, whether solid, liquid, or gaseous, both the substance which is selected as the standard substance is supposed to be at a definite temperature, as well as the body which is compared with the standard substance. Hence in determining the specific gravity of any substance by experiment, it is usually required to correct the observations so as to reduce the results to the standard temperatures, and in gases to the standard pressures, which have been once for all determined. The following examples will serve to show the mode in which this is usually accomplished.

(1.) By the hydrostatic balance (see **HYDROSTATICS**, page 56) the weight of a solid body in air was found to be p grammes, and its loss of weight in water = p grammes; the temperature during the experiment being t° . Find from this the specific gravity of the body at 0° , referred to water when at its greatest density, viz. at 4°C .

Let δ be the whole expansion of a unit volume of water, in being raised from 4° to t° , and let α be the coefficient of cubical expansion of the solid body. If we now suppose that the body maintains the temperature t° , while immersed in water, but that the water assumes its standard temperature of 4° , then the loss in the water would not have been p , but $p(1 + \delta)$. Again, if now the body would assume the normal temperature of 0° , its own volume would be diminished in the ratio of $1 + \alpha t : 1$, and the weight of the displaced water would diminish in the same ratio. The weight $p(1 + \delta)$ would thus become :

$$\frac{p(1 + \delta)}{1 + \alpha t};$$

and dividing the absolute weight of the body, p , by this weight of the displaced water, we obtain the corrected specific gravity :

$$\frac{p}{\frac{p(1 + \delta)}{1 + \alpha t}} = \frac{p(1 + \alpha t)}{p(1 + \delta)}.$$

(2.) In determining the specific gravity of a liquid with a specific gravity bottle (see **HYDROSTATICS**, page 75), the following data were obtained :

$$\begin{array}{ll} \text{Weight of the liquid at } t_1^\circ = P_1. & \\ \text{,, ,, water at } t^\circ = P. & \\ \text{U} & \end{array}$$

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Find from these data the specific gravity of the liquid at 0° , referred to water at 4° .

Let δ_1 = the expansion of the unit volume of the liquid from 0° to t_1° .

Let $\delta =$ " " " water " 4° to t° .

Let κ = the coefficient of cubical expansion of glass.

(a) If the liquid were at 0° , the weight of an equal volume would be $P_1 (1 + \delta_1)$.

(b) If the bottle also were at 0° , this weight would become less and be
$$\frac{P_1(1 + \delta_1)}{1 + \kappa t_1}.$$

(c) Similarly the weight of the water would have been

$$\frac{P(1 + \delta)}{1 + \kappa t}.$$

Hence sp. gr. = $\frac{P_1(1 + \delta_1)}{1 + \kappa t_1}$

$$\frac{1 + \kappa t_1}{P(1 + \delta)} = \frac{P_1}{P} \cdot \frac{(1 + \delta_1)(1 + \kappa t)}{(1 + \delta)(1 + \kappa t_1)}.$$

(3.) A gas has the volume v , weight P , pressure b , temperature t . Find its specific gravity, the weight of an equal volume of air at 760 millimetres pressure, and temperature 0° being unity. (.0012995 gramme = weight of 1 cubic centimetre air, at 760 millimetres, 0° C.)

The volume v becomes at 760 millimetres = $v \frac{b}{760}$.

At 0° this becomes $v \cdot \frac{b}{760} \cdot \frac{273}{273 + t}$.

If the gas were air, and v is in cubic centimetres, b in millimetres, it would have a weight of $v \cdot \frac{b}{760} \cdot \frac{273}{273 + t} \cdot .0012995$.

$$\therefore \frac{P}{v \frac{b}{760} \cdot \frac{273}{273 + t} \cdot .0012995} = \text{specific gravity of gas.}$$

(4.) Find the specific gravity of a gas from the following data:

The empty glass vessel weighs 837.356 grammes	} at 0° and 760 millimetres pressure.
Full of air it weighs . . . 848.201	
Filled with the gas it weighs 852.492	

What corrections would be required if the gas had been

at 18° C. and 730 millimetres pressure, when its weight was ascertained ?

The weight of the gas is :

$$852.492 - 837.356 = 15.136 \text{ grammes.}$$

The weight of the air is :

$$848.201 - 837.356 = 10.845 \text{ grammes.}$$

And both gases being under the same conditions of temperature and pressure, the specific gravity is simply :

$$\frac{15.136}{10.845} = 1.3956.$$

But if the gas would have been weighed at 18° , and 730 millimetres pressure, it would have been necessary to reduce the weight found to what it would have been at the normal conditions of temperature and pressure. If a is the co-efficient of dilatation of the gas, and the weight found at 18° , and 760 millimetres pressure, = P , while the weight at 0° is P^1 , then

$$P = P^1 (1 + 18 a),$$

or

$$P^1 = \frac{P}{1 + 18 a} = 15.136 \times \frac{76}{73} \times \frac{1}{1 + 18 a},$$

when corrected for pressure.

231. **Determination of the density of vapours.**—In Art. 156, p. 171, and Art. 157, p. 173, the methods used by Gay-Lussac and Dumas for determining the density of vapours have been described. The following two examples will serve to illustrate the methods numerically. It may be remarked, that in both these examples the density is referred to hydrogen as standard substance, the hydrogen being supposed to be at a temperature of 0° , and 760 millimetres pressure.

(1.) *Gay-Lussac's Method.*—In order to determine the density of the vapour of Penthane (C_5H_{12}), the following determinations were made :—

Weight of Penthane	0.101 gramme.
Temperature of the air	16° .
Temperature of the vapour	91° .
Volume of the vapour	59.5 cubic centimetres.
Height of barometer	752 millimetres.
Difference of mercurial levels	220 „

From these data it follows that the pressure of the vapour was equal to the barometric column of 752 millimetres at 16° diminished by a column of 220 millimetres at 91° . Both heights

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must thus first be reduced to the temperature of 0° , in order to subtract them from one another :

$$\text{External pressure of mercury : } \frac{752}{1 + (0.00018 \times 16)} = 749.9.$$

Pressure of mercury within the apparatus :

$$\frac{220}{1 + (0.00018 \times 91)} = 216.4.$$

The tension of the vapour in the apparatus was therefore :

$$749.9 - 216.5 = 533.5 \text{ millimetres.}$$

Now 59.5 cubic centimetres of Penthane weigh, at a pressure of 533.5 millimetres and a temperature of 91° , 0.101 gramme. Under the same conditions of temperature and pressure an equal volume of hydrogen would weigh :

$$\frac{0.00008936 \times 59.5 \times 533.5 \times 273}{760 \times (273 + 91)} = 0.0027992 \text{ gramme,}$$

since 1 cubic centimetre of hydrogen at 0° and 760 millimetres weighs 0.00008936 gramme. We have thus finally :

$$\text{Density of vapour required} = \frac{0.101}{0.0027992} = 36$$

on the hydrogen-scale.

(2.) *Dumas' Method.*—For determining the density of Hexane (C_6H_{14}) the following data were ascertained :

Weight of globe with air, at $15^\circ.5$. . . 23.449 grammes.

 " " vapour, at 110° . . . 23.720 "

Capacity of globe 178 cub. cent.

The pressure remained sensibly the same during the experiment ; hence no correction on account of pressure is required. The calculation is therefore simply as follows :

1 cubic centimetre of air at 0° weighs 0.001293 gramme ; hence the weight of 178 cubical centimetres at $15^\circ.5$ is :

$$\frac{0.001293 \times 178 \times 273}{273 + 15.5} = 0.218 \text{ gramme.}$$

The weight of the empty globe is therefore :

$$23.449 + 0.218 = 23.231 \text{ grammes ;}$$

and the weight of the vapour :

$$23.720 - 23.231 = 0.489 \text{ gramme.}$$

Now 1 cubic centimetre of hydrogen at 0° weighs 0.00008936 gramme ; hence at 110° the weight of 178 cubic centimetres

$$\text{is : } \frac{0.00008936 \times 178 \times 273}{273 + 110} = 0.01134 \text{ gramme.}$$

The required density of the vapour is therefore :

$$\frac{0.489}{0.1134} = 43.1$$

on the hydrogen-scale.

232. **Problems on temperature-corrections.**—1. In an experiment to determine the specific gravity of atmospheric air, as compared with water, a glass globe was used whose internal capacity was exactly 10 litres. When it was filled with dry air at a temperature of 18° C. and barometric pressure of 754 millimetres, it weighed 12.01 grammes more than it did after so much air had been pumped out that the pressure-gauge only indicated 5 millimetres pressure. Deduce from this the specific gravity of air at a temperature of 0° C. and 760 millimetres pressure.

First we must find the total original weight of air in the globe = x from the proportion :

$$x : 12.01 :: 754 : (754 - 5)$$

$$x = \frac{754}{749} \times 12.01 = 12.09 \text{ grammes.}$$

This weight reduced to the normal pressure of 760 gives

$$\frac{760}{754} \times 12.09 = 12.19 \text{ grammes ;}$$

and finally, correcting this weight for temperature, we obtain :

$$12.19 (1 + 18 \times 0.003665) = 12.995 \text{ grammes ;}$$

in other words, one litre of air at 0° and 760 millimetres weighs, according to this experiment,

$$1.2995 \text{ gramme ;}$$

and a cubic centimetre weighs at the normal conditions :

$$0.0012995 \text{ gramme.}$$

But a centimetre of water at the normal conditions (4° C.) weighs

$$1 \text{ gramme.}$$

Hence the specific gravity of air compared with water is by this experiment :

$$0.0012995 = \frac{1}{770} \text{ very nearly.}$$

It should, however, be remarked that the weight of 1 litre of air at 0° and 760 millimetres weighs in Paris (60 metres above the sea level)

$$1.293187 \text{ gramme ;}$$

while at any other latitude = ϕ , height above the sea level = h

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(in metres), temperature = t° C., pressure = p (in centimetres); and taking the mean radius of the earth = R as 63661998 metres, the weight of 1 litre of air must be calculated from the formula :
Weight of one 1 litre of air in grammes

$$= 1.29743 \times \frac{p}{(1 + 0.003665t)76} \times (1 - 0.00265 \cos 2\phi) \left(1 - \frac{2h}{R}\right).$$

The ratio of this weight to that of equal volumes of water and mercury may be expressed by the numbers :

$$\underbrace{1 : 773.28}_{\text{air}} : \underbrace{10513.5}_{\text{water}} : \underbrace{10513.5}_{\text{mercury}}$$

(2.) In England, formerly distilled water at a temperature of 60° F. was taken as standard of comparison for solid bodies, in determining specific gravities (see HYDROSTATICS, Arts. 70 and 71, on French and English standards); while gases have been compared with dry air at 60° Fahrenheit under a barometric pressure of 30 inches of mercury at 60° Fahrenheit. In France solids are compared with water at 4° C., the body compared being supposed to be at 0° C. Gases are also compared at 0° with either air or hydrogen at 0° , the pressure being 760 millimetres. If we wish to ascertain the weight of a given volume of gas in English units, taking advantage of Regnault's value for the weight of a cubic centimetre of air, as given in the preceding problem, we have to proceed as follows :

Suppose we wish to find the weight of 100 cubic inches of air in London at 60° F., the pressure being 30 inches, reduced to 60° F. We have—

(i) 1 French litre = 61.02705 English cubic inches.

(ii) 760 French millimetres = 29.914 inches at 32° F. in London.

(iii) 29.914 inches at 32° become at 60° F. (15° C.)
 $= 29.914 (1 + 15.5 \times 0.00018)$
 $= 29.997$ English inches at 60° F.

(iv) 1.29318 grammes = 19.9566 grains.

(v) The coefficient of expansion of air for 1° F. being = 0.00204, the density of the gas at 32° F. will be to its density at 60° in the proportion of

$$1 + 0.00204 \times 28 : 1, \text{ or} \\ 1.057 : 1.$$

Hence we obtain the weight of 100 cubic inches of air under the required conditions :

$$= 19.9568 \left(\frac{100}{61.02705} \right) \left(\frac{30}{29.997} \right) \left(\frac{1}{1.057} \right) = 30.94 \text{ grains.}$$

(3.) The weight in vacuo, at 62°F. , of a given volume of purified mercury was found by Professor Balfour Stewart to be to the same volume of water in the ratio of

$$13590.86 : 1001.62,$$

both determinations being made in grains. What is, according to this experiment, the specific gravity of mercury at 0° referred to water at 4°C. ?

Since $62^{\circ}\text{F.} = 16^{\circ}.6\text{C.}$, a unit volume of mercury at 0°C. will become at $62^{\circ}\text{F.} = 1 + 0.00018 \times 16.6 = 1.00298$. It follows that the weight of the same volume of mercury would be at 0°

$$13590.86 (1.00298) = 13631.361 \text{ grains.}$$

Next, a volume of water which is = 1 at 4° will become 1.0011437 at $16^{\circ}.6$ (see Kopp's table, page 69); hence the above weight of water would become, at 4°C. ,

$$1001.62 (1.0011437) = 1002.766 \text{ grains.}$$

$$\text{Hence specific gravity} = \frac{13631.361}{1002.766} = 13.594.$$

(4.) In order to determine the specific gravity of platinum and copper, a piece of each metal was weighed in air and then in water, the temperature during the experiment being 20°C. By simply dividing the weight in air by the loss of weight in water, the specific gravity was found, without applying any corrections,

$$\text{Of platinum} = 23.055.$$

$$\text{Of copper} = 8.893.$$

Find the true specific gravity of both metals at 0° compared with water at 4° , and taking into account the loss of weight in air (reduction of weight in air to the weight in vacuo).

$$\begin{array}{llll} \text{Given : Specific gravity of air at } 20^{\circ} & . & . & . & 0.0012. \\ & \text{,,} & \text{,,} & \text{water} & \text{,,} & . & . & . & 0.99827. \end{array}$$

To find a general answer let

m = the weight of body in air ;

l = the weight of the displaced air ;

w = the weight of the displaced water (the difference between the weight in air and the weight in water) ;

q = the specific gravity of the water during the experiment ;

λ = the specific gravity of the air during the experiment, referred to water at 4°C. ;

s = the specific gravity of the body at the temperature of the experiment referred to water at 4°C.

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The weight of the body in vacuo is :

$$m + l ;$$

the weight of the water in vacuo is :

$$w + l ;$$

the weight of the displaced water (at 4° C.) is :

$$\frac{w + l}{Q}.$$

Hence the specific gravity of the body at the temperature of the experiment :

$$s = \frac{m + l}{w + l} Q \quad . \quad . \quad . \quad . \quad (I).$$

The weight of the displaced air is :

$$\frac{w + l}{Q} \lambda = l ;$$

or .

$$l = \frac{w \lambda}{Q - \lambda} ;$$

and substituting this value in equation (I) we obtain :

$$s = \frac{m}{w} (Q - \lambda) + \lambda \quad . \quad . \quad . \quad . \quad (II).$$

By employing the numerical values given in the question, we have for platinum :

$$\begin{aligned} s &= 23.055 (0.99827 - 0.0012) + 0.0012 \\ &= 22.988 ; \end{aligned}$$

for copper :

$$\begin{aligned} s &= 8.893 (0.99827 - 0.0012) + 0.0012 \\ &= 8.868. \end{aligned}$$

Dividing each of these specific gravities by the factor $(1 + 20a)$, in which a is the coefficient of cubical expansion of each metal, we obtain the true specific gravity of each substance at 0°, compared with water at 4° C.

233. Expansion of alloys.—Alloys have, as determined by Matthiessen (at least between 0° and 100°), at an elevation of temperature, the same volume which the sum of the components would assume if they had expanded independently. Thus, if v° is the volume of the alloy, v_1° the volume of one constituent, and v_2° the volume of another constituent ; and β , β_1 , β_2 , are the coefficients of expansion, then at the temperature t :

$$v^\circ (1 + \beta t) = v_1^\circ (1 + \beta_1 t) + v_2^\circ (1 + \beta_2 t).$$

$$\text{Since } v^\circ = v_1^\circ + v_2^\circ$$

$$\therefore v^\circ + v^\circ \beta t = v_1^\circ + v_1^\circ \beta_1 t + v_2^\circ + v_2^\circ \beta_2 t ;$$

$$\begin{aligned} \text{or} \quad v^\circ \beta t &= v_1^\circ \beta_1 t + v_2^\circ \beta_2 t \\ \therefore \beta &= \frac{v_1^\circ \beta_1 + v_2^\circ \beta_2}{v_1^\circ + v_2^\circ}; \end{aligned}$$

that is, β is the arithmetical mean between β_1 and β_2 .

234. **Correction of fixed points in thermometers.**—As has been shown in Chapter II., the fundamental distance between the freezing and boiling point in a thermometer is divided into a certain number of equal portions, called degrees. On the centigrade thermometer there are 100 such equal divisions. If neither the freezing point nor the boiling point be correctly marked, or only one of them is correct, the readings of the instrument will require a correction, and in order to ascertain the correction the fixed points of a thermometer should be compared from time to time with a standard thermometer. If the correction of the fixed points is ascertained, its application to the readings will become apparent from the following considerations.

(1.) Let the freezing point alone be wrongly marked, and let the correct zero of the scale be at the reading $\pm a^\circ$; in other words, let the *marked* zero point be too low or too high by a degrees. At $\pm a$ degrees of the scale there should thus be 0 marked, if the thermometer is to give correct readings; hence denoting by c correct degrees and by f incorrect degrees:

$$100c = (100 \mp a)f$$

$$\therefore 1 \text{ incorrect degree} = \frac{100}{100 \mp a} \text{ correct degrees};$$

$$\text{and } n \text{ incorrect degrees} = \frac{100n}{100 \mp a} \text{ correct degrees.}$$

If the incorrect thermometer reads $t^\circ = 100^\circ - (100^\circ - t')^\circ$, then the correct thermometer would indicate

$$t^\circ = 100^\circ - \frac{100}{100 \mp a} (100 - t')^\circ = \frac{t' \mp a}{100 \mp a} 100 \text{ C.}$$

where the upper sign is to be taken when a was positive, and the lower when a was negative.

The absolute value of a will always be very small; in any case it will always be less than 100, and the denominator of this fraction will thus always be a positive quantity. Hence, if the zero of the scale is too low—that is, when a is positive and the upper sign must be taken—then t is positive as long as t' is positive and greater than a ; $t = 0$, when $t' = a$; and finally, t is negative both when t' is negative and when t' , though positive, is less than a .

Again, if the zero of the scale is too high—that is, when a is

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negative and the lower sign is to be taken—then t is positive, both when t' is positive and when negative, provided the absolute value of t' is less than the absolute value of a ; $t = 0$, when the absolute value of the negative t' is equal to the absolute value of a ; finally, t is negative when t' is negative, but its absolute value is greater than the absolute value of a .

In any case when t' is positive, and $\left. \begin{array}{l} \text{greater than} \\ \text{equal to} \\ \text{less than} \end{array} \right\} 100$, then t is

also positive and $\left. \begin{array}{l} \text{greater than} \\ \text{equal to} \\ \text{less than} \end{array} \right\} 100$.

Examples :

$a = +10$; then $t = \frac{10(t' - 10)}{9}$, and we have the corresponding values :

(wrong) $t' = 117 \quad 100 \quad 18 \quad 10 \quad 4 \quad 0 \quad -10 \quad -18$

(correct) $t = 118\frac{2}{9} \quad 100 \quad 8\frac{2}{9} \quad 0 \quad -6\frac{2}{3} \quad -11\frac{1}{9} \quad -22\frac{2}{9} \quad -31\frac{1}{9}$

$a = +1$; then $t = \frac{100(t' - 1)}{99} = 1\cdot01(t' - 1)$, and :

$t' = 117 \quad 100 \quad 18 \quad 1 \quad 0 \quad -1 \quad -18$

$t = 117\cdot16 \quad 100 \quad 17\cdot17 \quad 0 \quad -1\cdot01 \quad -2\cdot02 \quad -19\cdot19$

$a = -1$; then $t = \frac{100(t' + 1)}{101} = 0\cdot99(t' + 1)$, and :

$t' = 117 \quad 100 \quad 18 \quad 0 \quad -1 \quad -18$

$t = 116\cdot82 \quad 100 \quad 18\cdot81 \quad 0\cdot99 \quad 0 \quad -16\cdot83$

$a = -10$; then $t = \frac{10(t' + 10)}{11} = 0\cdot909(t' + 10)$, and :

$t' = 117 \quad 100 \quad 18 \quad 0 \quad -4 \quad -10 \quad -18$

$t = 115\cdot443 \quad 100 \quad 25\cdot452 \quad 9\cdot09 \quad 5\cdot455 \quad 0 \quad -7\cdot272$

(2.) Let it be supposed that the freezing point is correctly fixed, but that a correction is necessary because the boiling point is wrongly marked. The error consists here in this, that the temperature denoted upon the scale by 100° will not correspond to a pressure of aqueous vapour of 760 millimetres, but will correspond to any other pressure, which we may denote by b . Hence, if b is greater than 760 millimetres the thermometer indicates the temperature too low, but when b is less than 760 millimetres the temperature indicated by the thermometer will be higher than the correct temperature.

To correct the wrong temperature t' , indicated by the thermometer, into the correct reading t , we must ascertain from the tables what temperature τ corresponds to the pressure of saturated vapour b , and hence we find from the proportion :

$$100 : t' :: \tau : t, \text{ that} \\ t = 0.01 \times \tau \times t'$$

It follows that :

$$\begin{array}{c} > \\ \text{when } b = 760, \text{ then } T = 100, \text{ and therefore } t = t', \text{ and } t' = t, \\ < \end{array}$$

in other words :

when $b > 760$, then $t' < t$, and the temperature indicated is too low ;

„ $b = 760$, „ $t' = t$, „ „ „ „ „ correct ;

„ $b < 760$, „ $t' > t$, „ „ „ „ „ too high.

For negative temperatures their absolute values are to be taken.

Examples :

$b = 906.410$ millimetres corresponds to $\tau = 10.5$ (Table I., p. 167).

∴ $t = 1.05$ t' ; thus if $t' = \pm 16.8$, $t = \pm 17.64$.

$b = 766.786$; then $\tau = 102.318$ (by interpolation);

∴ $t = 1.023$ t' ; thus if $t' = \pm 12$, $t = \pm 12.278$.

$b = 687.828$; $\tau = 97.143$; $t = 0.971$ t' ; thus if $t' = \pm 15.375$,

$$t = \pm 14.936.$$

$b = 633.692$; $\tau = 95$; $t = 0.95$ t' ; thus if $t' = \pm 20$, $t = \pm 19$.

If the thermometer immersed in vapour of boiling water indicates a temperature τ_1 , while the barometric pressure is at the same time b_1 millimetres, then the correct temperature corresponding to the pressure b_1 must be ascertained. Let this temperature be τ . Then $\tau = 0.01 \tau_1$.

$$\tau = \frac{100 \tau}{\tau_1} \quad \text{and} \quad t = \frac{\tau}{\tau_1} t'$$

Thus let $\tau_1 = 94.942$ and $b_1 = 687.828$; then to the latter pressure corresponds, by the tables, 97.143 , hence $\frac{\tau}{\tau_1} = \frac{97.143}{94.942}$

1.02318

∴ $\tau = 102.318$ (corresponding to 766.786 millimetres),

and $t = 1.02318$ τ_1

which gives the correction generally.

(3.) If both fixed points are wrong, then both corrections must be ascertained, and as formula of reduction for wrong

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readings into correct ones we have the formula, using the same notation :

$$t^{\circ} = \frac{(t' \mp a)}{100 \mp a} \tau^{\circ}$$

For let us suppose that we have two thermometers of exactly the same dimensions, one having its fixed points correctly marked, the other having them both wrong. Then if d is the distance between the two points marked 0° and 100° on the wrong scale, and l is the distance of the true zero point from the mark 100° ,

then $l = \tau$ correct degrees

and one wrong degree $= \frac{d}{100} = \frac{l+a}{100}$ incorrect degrees,

$$= \frac{\tau}{100} \text{ correct } \pm \frac{a}{100} \text{ incorrect degrees.}$$

$$\therefore \text{ One incorrect degree} = \frac{\tau}{100 \mp a} \text{ correct degrees.}$$

$$\text{But } t \text{ correct degrees} = (t' \mp a) \text{ incorrect degrees.}$$

$$= \frac{(t' \mp a) \tau}{100 \mp a} \text{ incorrect degrees.}$$

which proves the formula.

We may check this formula by applying it to the two cases when only one of the fixed points is wrong.

When $t' = \pm a$, then $t = 0$; when $t' = 100$, then $t = \tau$.

When $\tau = 100$, then the boiling point is correct and $t = \frac{t' \mp a}{100 \mp a} \times 100$, that is, the formula becomes the same as that used for the correction if the freezing point is wrong.

When $a = 0$, then the freezing point is correct, and the formula becomes $= \frac{\tau t'}{100} = 0.01 \tau \times t'$, the same as used for the correction when the boiling point is wrong.

Examples :

Let $a = +1$, and $\tau = 102^{\circ}.318$. Then $t = \frac{t' - 1}{99} \times 102^{\circ}.318$, and we find the following corresponding correct readings from the incorrect ones :

t'	118	100	20	1	0	-1	-20
t	120.921	102.318	19.637	0	-1.034	2.067	-21.704

Let $a = -1$, $\tau = 98.7$. Then $t = \frac{t' + 1}{101} \times 98.7$, and we obtain:

t'	118	100	20	1	0	-1	-20
t	116.29	98.7	20.522	1.954	0.977	0	-18.567

235. **Calibration of a thermometer.**—It has already been pointed out in Art. 28, p. 21, that in a good thermometer it is necessary to calibrate the tube, that is to say, to compare the volumes which correspond to the divisions of the scale at different places, and it was explained, in general terms, that for this purpose a thread of mercury, separated from the rest, is made use of. The thermometer is turned upside down and a slight tap given against the end. Then either a thread will separate, or the whole of the mercury will flow down, separating from the walls of the bulb at some point. The separation is usually determined by a microscopical air-bubble adhering to the glass, which expands to a larger size. If the mercury separate in the bulb, we try, by suddenly turning the thermometer upright, to make the bubble formed there rise to the opening of the stem; this can always be done, with patience. The mercury then divides at the opening of the tube.

Suppose the thread to be too long, say p degrees longer than was desired. The bulb is warmed while the thread is separated; the air is pushed forward by the rising mercury. Then the thread is made to run back to the rest of the mercury, and the position of its upper end is observed at the instant of meeting. The little bubble of air remains adhering to the glass at the point of the stem where the junction took place. The thermometer is now cooled p degrees, and again reversed and shaken, when a thread of the desired length is separated. If, on the other hand, the thread be p degrees too short, it is united to the rest, and the thermometer warmed p degrees, when the desired length will break off. Even if this manipulation should not succeed at first, it always will, on repetition, be possible to get a thread accurately of any length to the fraction of a degree. For very short threads, however, the process often fails; so that, in such a case we must make use of combined observations with threads of different lengths.

By gentle inclining and shaking, one end of the thread can be adjusted to any desired division with great accuracy. In accurate observations, especially with the telescope, it is sufficient to place it nearly on the division, and estimate the tenths of a degree at both ends of the thread. Since the thread of mercury and the graduation are not in the same plane, we must avoid parallax when reading off. It is simplest to lay the thermometer upon a piece of looking-glass, and place the eye so that its image coincides with the division to be read; or a lens is fixed steadily and the thermometer is pushed along parallel to itself under it. The greatest accuracy is secured by reading with the telescope.

The above formula for the calculation follows from the following considerations. The thread of mercury used for the observations laid end to end n times, takes up the volume of the tube from division 0 to 100, increased by $\delta_1 + \delta_2 + \dots + \delta_n$. But since 0° is at division p_0 , and 100° at division $100 + p_1$, the increase of the volume of mercury from division 0 to division 100 answers to an increase of temperature at $103 + p_0 - p_1$, so that the increase of the volume equal to the length of the thread means an increase of temperature—

$$\frac{100 + p_0 - p_1 + \delta_1 + \delta_2 + \dots + \delta_n}{n} = a + a$$

therefore a rise of the mercury

from 0 to a corresponds to an increase of temperature $a + a - \delta$;

$$,, a,, 2a \quad ,, \quad ,, \quad ,, \quad ,, \quad a + a - \delta_2;$$

and finally,

from division o

Temperature increase.

to a

$$a + \frac{1}{2} | a - \delta,$$

to 2a

$$2a + \quad 2a - \delta_1 - \delta_2$$

to *ma*

$$ma + |ma - \delta_1 - \delta_2 \dots - \delta_m|$$

The expressions to the right of the vertical line would be the thermometer corrections, if the division 0 also meant the temperature 0° . Since the temperature $-p_0$ corresponds to this, p_0 must be subtracted from each of them.

Example.—A thermometer graduated up to the boiling point of mercury is to be calibrated at intervals of 50° , which is enough for ordinary purposes. Here, therefore, $n = \frac{100}{50} = 2$. A thread of about 50° long was separated, and occupied the spaces—

from 0.0 to 50.9

$$\delta_1 = +0.9$$

„ 50°0 „ 100°4

$$\delta_2 = +0.4$$

100°I 150°3

$$\delta_3 = +0.2$$

149.8 199.8

$$\delta_4 = +0.0$$

200°4 250°0

$$\delta_3 = -0.4$$

In addition the temperature 0° was found to be at the division $+0.6$ and 100° at 99.7 ; therefore

$$p_0 = +0.6; p_1 = -0.3$$

Therefore—

$$a = \frac{p_0 - p_1 + \delta_1 + \delta_2}{n} = \frac{+0.6 + 0.3 + 0.9 + 0.4}{2} = +1.1.$$

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The table of corrections is therefore—

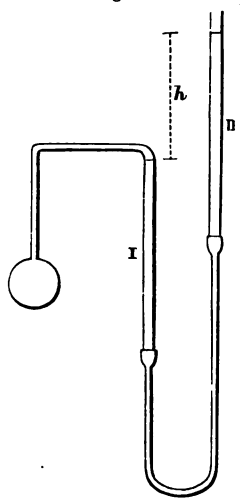
Division..	Correction.
0 0·6	= - 0·6
50 1·1 - 0·6 - 0·9	= - 0·4
100 2·2 - 0·6 - 0·9 - 0·4	= + 0·3
150 3·3 - 0·6 - 0·9 - 0·4 - 0·2	= + 1·2
200 . + 1·2 + 1·1 - 0·0	= + 2·3
250 2·3 + 1·1 + 0·4	= + 3·8, &c.

The correspondence of the calculated correction for 100 with the independent determination of the boiling point furnishes a partial-proof of the accuracy of the calculation.

From the last column the correction of any intermediate division is interpolated according to the ordinary rules. For example, to the reading 167·3, the temperature $167·3 + 1·6 = 168°·9$ would correspond.

236. **The Air-thermometer.**—In Article 40, page 31, it was already shown how air may be used as a thermometric substance.

Fig. 86.



The scientific definition of temperature rests upon the assumption that a perfect gas (e.g. dry air) expands, at constant pressure, proportionally to the rise of temperature. The expansion amounts for each degree to 0·003665 of the volume at 0°; or what is identically the same, the pressure of a quantity of air kept at a constant volume increases for each degree of rise of temperature by 0·003665 of its pressure at 0°.

A very simple form of modern air-thermometer is that of *Jolly*. It depends on the law just enunciated. A glass globe, *fig.* 86, of about 50 cubic centimetres capacity, filled with dry air, is in communication, by means of a capillary tube, with a vertical glass tube, I, in which the air is confined by mercury. By the raising or lowering of the surface of the mercury in II,

which is joined to I by an india-rubber tube, the surface of the mercury in I can be brought to a mark near the opening of the capillary tube.

To graduate the instrument, the bulb is surrounded by melting ice, just as in determining the freezing point on the stem of a thermometer, the mercury is adjusted, and the height of

the barometer b_o , and the height h_o , of the mercury in II above that in I observed. We will call $b_o + h_o = H_o$, where h_o is negative when the surface in II is lower. All the heights b and h must be reduced to 0° .

If, now, any other temperature t which is to be measured, be communicated to the air in the bulb, the mercury adjusted to the mark, and the heights b and h be observed, calling $b + h = H$, we have

$$t = \frac{H - H_o}{0.003665 H_o - 3\beta H}$$

where 3β denotes the cubical expansion of glass. Where this is not known for the sort of glass used, we may take $3\beta = 0.000025$. Up to temperatures of about 60° we may calculate it with sufficient accuracy by the more convenient formula—

$$t = 275 \times \frac{H - H_o}{H_o}$$

It is here assumed that the volume of the capillary tube up to the mark to which the mercury is adjusted may be completely neglected in comparison with that of the bulb. If not, we must add to the value of t , given above, the correction—

$$t \times \frac{v'}{v} \times \frac{H}{H_o} \times \frac{1}{1 + 0.003665 t'}$$

where v = volume of the bulb,

v' = volume of the connections to the mark,

t' = temperature of the room.

The ratio $\frac{v'}{v}$ is found by weighing with mercury. If p be the weight of the mercury in the bulb alone, and p the weight when the apparatus is filled up to the mark—

$$\frac{v}{v'} = \frac{p - p}{p}$$

The truth of the above formulæ follows from the following considerations. The quantity of air remains constant. If v be the capacity of the bulb at 0° , d_o the density of the air at 0° and 760 millimetres pressure, the quantity of air is given at the first observation, denoting 0.003665 by a , by—

$$\frac{d_o H_o}{760} \left(v + \frac{v'}{1 + a t'} \right);$$

at the second by—

$$\frac{d_o H_o}{760} \left[\frac{v(1 + 3\beta t)}{1 + a t} + \frac{v'}{1 + a t'} \right].$$

x

By equating these expressions, dividing by $\frac{d_0}{760}$, and multiplying both sides by $\frac{1+a t}{v}$, we get—

$$H_0(1+a t)\left(1+\frac{v'}{v} \cdot \frac{1}{1+a t'}\right)=H\left(1+3 \beta t+\frac{v'}{v} \cdot \frac{1+a t}{1+a t'}\right)$$

or, separating t —

$$t\left[a H_0-3 \beta H-\frac{v'}{v} \cdot \frac{a}{1+a t'} \cdot (H-H_0)\right] \\ =\left(H-H_0\right)\left(1+\frac{v'}{v} \cdot \frac{1}{1+a t'}\right).$$

From this we get the first of the expressions given above by putting $\frac{v'}{v}=0$.

In order to obtain the correction, we write the left-hand side of the equation—

$$t\left(a H_0-3 \beta H\right)\left(1-\frac{v'}{v} \cdot \frac{1}{1+a t'} \cdot \frac{H-H_0}{a H_0-3 \beta H}\right).$$

In the factor of the small magnitude $\frac{v'}{v}$ we may neglect the $3 \beta H$ which occurs in the denominator, in comparison with $a H_0$, and finally we obtain as above—

$$t=\frac{H-H_0}{a H-3 \beta H}\left(1+\frac{v'}{v} \cdot \frac{H}{H_0} \cdot \frac{1}{1+a t'}\right).$$

237. Comparison of Mercury and Air-thermometers.—Mercury does not expand proportionately to the temperature as measured by an air-thermometer. Its volume at the temperature t may be expressed thus—

$$v=v_0\left(1+0.00017905 t+0.000000252 t^2\right) ;$$

or up to $t'=100$ by—

$$\log . v_1=\log . v_0+0.000078 t,$$

an expression which is frequently very convenient. According to this, the readings of the common mercurial thermometer, when they have been corrected, as shown in Arts. 233 and 234, are between 0° and 100° lower; above 100° , on the contrary, higher than those of an air-thermometer, although, on account of the simultaneous expansion of the glass, they are less than would follow from the formula given above. Up to 150° the deviation usually remains smaller than 0.5° ; up to 250° it may

amount to 4° ; up to 350° to 10° . On the average the correction of a mercurial thermometer to an air-thermometer may be taken as about—

for reading—

0 20 30 60 80 100 150 200 250 300 ;

correction—

± 0.0 ± 0.2 ± 0.3 ± 0.3 ± 0.2 ± 0.0 -0.5 -1.1 -2.4 -3.3 .

238. **Siemens' Pyrometer.**—On the principle that the electric resistance of a metallic conductor is altered when the temperature changes, a very practicable form of pyrometer has been introduced by Dr. Siemens. The electrical conductivity of metals in general is diminished by an increase of temperature, and as the resistance is inversely proportional to the conductivity, the resistance becomes greater as the temperature rises. It is shown in the treatise on **ELECTRICITY** in this series, Art. 377, p. 235, how the electrical resistance of a metal may be compared with that of another by means of an apparatus called Wheatstone's bridge. A coil of known resistance is placed in the particular locality whose temperature is to be observed, and is connected by means of long conducting wires with the place of observation, where it forms part of a Wheatstone's bridge arrangement. The resistance of the coil is known in terms of the reostat (see **ELECTRICITY**, Art. 377a, p. 236), and by preliminary trials it has been ascertained how much additional wire must be introduced to balance a given increase in the temperature of the resistance coil. This being known, and the apparatus adjusted at the ordinary temperature, when the temperature of the resistance coil varies, this variation is at once known by observing the quantity which must be brought in or out of the reostat to produce equivalence. The apparatus has done great service in watching the temperature of large coils of telegraph wire which, stowed away in the hold of vessels, are very liable to become heated. It might also be used for the continuous and convenient observation of underground and submarine temperatures. If a coil of platinum wire were substituted for the copper, the apparatus could be used for observing the temperature of the interior of a furnace.

239. **Practical determination of the specific heat of substances.**—The general principles which have been enunciated in Chapter VI. on the methods of calorimetry may for practical purposes be summarised and applied in the following manner :—

1. If heat is conveyed to a body, it expands the more, the

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more heat is conveyed to it. Whatever heat is, the *quantity* of heat which a body contains *more* in one state than in another must be *definite* and connected with the change from one state to the other.

2. For a definite rise of temperature two different substances of equal mass require unequal quantities of heat. The substance which requires more heat is said to have a *greater capacity* for heat.

3. If the quantity of heat required to raise 1 gramme of water from 0° to 1° be called the thermal unit, then the number which expresses how many such units are required for raising a gramme of any other substance from 0° to 1° is called the specific heat of that substance.

4. If Q = quantity required to raise a body of weight P through t° , and H is the specific heat of that body, then

$$Q = H P t ;$$

that is, the quantity is proportional to the specific heat, to the weight, and to the increase of temperature required.

5. The specific heat of the unit of volume means the quantity required to raise 1 cubic centimetre of water or of any other substance from 0° to 1° . Clearly, if the heat required to raise 1 cubic centimetre of water from 0° to 1° is unity, the heat required to raise the unit volume of any other substance will be its specific heat multiplied by its specific gravity, or $H' = H s$, s denoting the specific gravity of the substance.

$$\text{But } s = \frac{P}{V} . \therefore H' = \frac{H P}{V} \text{ or } H P = H' V ,$$

and hence the quantity of heat required to raise a given *volume* through t° is—

$$Q = H' V t .$$

6. Let P, P' be two weights of the *same* substance, t, t' their temperature, then experiment proves that after mixing an intermediate temperature T is obtained. Supposing that no loss of heat occurs during mixing, and that the specific heat of the substance is the same for all temperatures, then—

$$(P + P') T = P t + P' t' ,$$

$$\text{or } T = \frac{P t + P' t'}{P + P'} .$$

The quantity of heat given off by one substance must be equal to that received by the other substance, provided the specific heat is the same for all temperatures, and if $t > T > t'$,

$$\text{then } P(t - T) = P'(T - t') .$$

7. Let now P, P' be the weights of different substances, having different specific heats H, H' . The temperature of the mixture will clearly approach more to the temperature of the body with greater specific heat and greater mass. The equation between the received and lost heat requires—

$$H P (t - T) = H' P' (T - t'); \dots \dots \dots (1)$$

therefore $t - T$ becomes smaller in the same proportion as $H P$ is greater than $H' P'$.

From the above we obtain—

$$H = H' \frac{P' (T - t')}{P (t - T)},$$

which gives the specific heat of one body when that of the other is known. For H' water with specific heat = 1 is taken.

8. If we suppose that H', P', t' refer to water, and H, P, t to the body, of which the specific heat is to be determined, then $H P (t - T)$ represents the quantity of heat given off by the body. But this heat is not all received by the water, for part of it goes to the thermometer, part to the vessel employed in the experiment.

(1) Let v = weight of vessel, v' its specific heat. Since it is at first at t' (the temperature of the water) and then at T , it receives—

$$v v' (T - t') \text{ units of heat.}$$

(2) Let the glass of the thermometer weigh g , and let its specific heat be g' , then it receives—

$$g g' (T - t') \text{ units.}$$

(3) Let the weight of the mercury be m , specific heat m' , then it receives—

$$m m' (T - t') \text{ units.}$$

Hence the equation (1) becomes—

$$H P (t - T) = (H' P' + v v' + g g' + m m') (T - t'),$$

$$\text{or } H = \frac{H' P' + v v' + g g' + m m'}{P} \cdot \frac{T - t'}{t - T}.$$

9. Three independent experiments are therefore required to determine the specific heat of the substance of the vessel, of the glass, and the mercury.

(1) Let a weight v' of the substance of the vessel be placed in the calorimeter at the temperature t .

$$\text{Then } v' v' (t - T) - v v' (T - t') = (P' + g g' + m m') (T - t').$$

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(2) A weight of glass g' is now placed in the calorimeter, and we have similarly—

$$g' g' (t - T) - g g' (T - t') = (P' + v v' + m m') (T - t').$$

(3) Finally, a weight of mercury, m' , is proceeded with in the same manner, and we obtain—

$$m' m' (t - T) - m m' (T - t') = (P' + g g' + v v') (T - t').$$

We have thus three equations with three unknown quantities, viz., v' , g' , m' , which may thus be calculated.

The value $v v' + g g' + m m' = w$ is called the *Water-equivalent* of the calorimeter and thermometer, for this value expresses the quantity of water which would have received the same increment of heat as the calorimeter and thermometer.

We have therefore—

$$H = \frac{(P' + w) (T - t')}{P (t - T)}.$$

10. When the calorimeter receives heat from the heated body, and its temperature thus rises above the surrounding objects, it loses at once heat by radiation, and the final temperature is less than it ought to have been if no loss had taken place. This heat must therefore be observed and taken into account. If this heat could have raised the calorimeter through N degrees, then the increase of temperature of the calorimeter would have been $T + N - t'$; hence the formula corrected stands thus—

$$H = \frac{(P' + w) (T + N - t')}{P (t - T)}.$$

Practically, the loss may be avoided by making a preliminary trial, to see approximately by how much the temperature of the water in the calorimeter will be raised by the introduction of the hot body. If it is raised through θ degrees, then select the water-temperature, so that it may be $\frac{1}{2} \theta$ degrees below the temperature of the surrounding air. The temperature of the mixture will then be $\frac{1}{2} \theta$ higher, and what is then lost will have been received at first.

The actual loss by radiation may however be determined by direct experiment.

Suppose q the loss of heat.

Then, by the preceding principles,

$$H P (t - T) = (P' + w) (T - t'') + q$$

where t'' = temperature of air, and the remainder of the notation the same as before.

Take now a weight P'' of a body of known specific heat H'' , so that

$$P'' H'' (t - T) = (P' + w) (T - t''),$$

and throw it into the same quantity of water; we shall then have a temperature of the mixture T' , which will differ from t only very little, and we shall have

$$P'' H'' (t - T') = (P' + w) (T' - t'') + Q,$$

from which
$$Q = (P' + w) \frac{(T - T') (t - t'')}{t - T}.$$

11. *Calorimeter with ice.*—Here the fall of temperature is due to the ice, and its conversion into water. The quantity of heat $H P t$ is expended in the melting of ice, the resulting water having the weight p . If another body gives $H' P' t' = p'$

$$\therefore \frac{H P t}{H' P' t'} = \frac{p}{p'} \text{ or } H = H' \frac{P' t' p}{P t p'};$$

but for water

$$H' P' t' \times 79.5 = p'$$

$$\therefore H = 79.5 \frac{p}{P t}.$$

12. *Method of Cooling.*—A body which cools loses heat at first rapidly, then more and more slowly. But for a small difference of temperature τ , the loss of heat $H P \tau$ may be considered uniform. If the time required for the loss is ζ , then

$$P H \tau = a \zeta, \text{ or } \zeta = \frac{P H \tau}{a},$$

where a is a constant, which depends on the temperature t of the body and the nature of the surface which loses heat. If the cooling proceeds from t to t' , then z' , the whole time, will be the sum of all the quantities $\left(P H \frac{\tau}{a} \right)$,

or
$$z' = \Sigma \left(P H \frac{\tau}{a} \right),$$

which is proportional to the weight of the body and the specific heat. Let now a vessel (weight p , specific heat h), be filled successively with weights P, P' , of the substances, whose specific heat is H, H' respectively. Observe the times, z, z' , it takes for the same amount of cooling from t to t' degrees; then since $\Sigma \left(\frac{\tau}{a} \right)$ is constant, we have

$$z = (P H + p h) \Sigma \frac{\tau}{a},$$

and

$$z' = (P' H' + p h) \Sigma \frac{\tau}{a},$$

from which

$$H = H' \frac{P' z}{P z'} + h \frac{p}{P} \left(\frac{z}{z'} - 1 \right)$$

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240. **Problems on specific heat.**—1. A pound of mercury, at the temperature of 100° , is mixed with 1 lb. of water at 7° C. The temperature of the mixture is found to be 10° . Find from this the specific heat of mercury.

Here we have, calling the specific heat x —

$$1 \times 7 + 100 \times x \times 1 = 1 \times 10 + 1 \times x \times 10$$

$$x = \frac{1}{30};$$

or since $10 - 7 =$ heat received by the water

and $(100 - 10) x =$ heat given up by the mercury,

$$\therefore 10 - 7 = (100 - 10) x$$

$$\therefore x = \frac{1}{30}, \text{ as before.}$$

2. Given two substances, at the temperatures t_1 , t_2 , respectively, and having the specific heats h_1 and h_2 . If a mixture is to be made of both, weighing p pounds and having a temperature t° , how much of each substance must be taken?

Let x , y , be the quantities of each substance required. Then—

$$(I) \quad x + y = p.$$

$$(II) \quad h_1 \times x \times (t^{\circ} - t_1) = h_2 \times y \times (t_2 - t^{\circ}).$$

because the heat lost by one substance must be equal to that gained by the other. Hence, solving the two equations, we obtain—

$$x = \frac{h_2 p (t_2 - t^{\circ})}{h_1 (t^{\circ} - t_1) + h_2 (t_2 - t^{\circ})}$$

$$y = \frac{h_1 p (t^{\circ} - t_1)}{h_1 (t^{\circ} - t_1) + h_2 (t_2 - t^{\circ})}$$

3. A sphere of copper, which weighs 3 lbs., is heated to 100° , and then placed in Laplace's calorimeter. The water discharged weighs 0.38 lb. Find from this the specific heat of copper.

Taking 80 thermal units as the quantity required to melt 1 lb. of ice, then 0.38 lb. requires

$$0.38 \times 80 \text{ units.}$$

The copper gives up this quantity, that is, it loses

$$3 \times 100 \times x \text{ units}$$

if x is the specific heat of copper; hence—

$$0.38 \times 80 = 3 \times 100 \times x$$

$$x = 0.10133.$$

4. A spherical balloon of 0.14 metre radius is filled with mercury at 70° . The mercury is then poured into water at its greatest density, which fills half of a cylindrical vase, 0.40

metre high and having a diameter of 0.40 metre. What will be the temperature of the mixture? (Specific gravity of mercury 13.59, coefficient of expansion 0.00018024, and specific heat of mercury 0.033.)

(a) Volume of balloon = $\frac{4}{3} \pi r^3 = 4 \times 1.047 \times 2.744$ decimetres = 11.494 cubic decimetres.

Density of mercury at $70^\circ = \frac{13.59}{1 + 0.00018024 \times 70} = 13.4107$.

Weight of the mercury = $11.494 \times 13.4107 = 154.142$ kilogrammes.

(b) Volume of the water = $\frac{\pi R^2 h}{2} = \frac{3.1416 \times 4 \times 4}{2} = 25.133$ cubic decimetres.

Weight of this water 25.133 kilogrammes.

If x be the temperature of the mixture, the heat received by the water is

$$25.133 (x - 4) \quad \dots \quad (I),$$

and that lost by the mercury

$$154.142 (70 - x) \cdot 0.033 \quad \dots \quad (II),$$

equating (I) or (II), $x = 15.2^\circ$.

5. A sphere of platinum of 0.05 metre radius, at 95° C., is plunged into two litres of water at 4° C. Find the temperature of the mixture. (Specific gravity of platinum 22.01; specific heat 0.0324; coefficient of dilatation 0.00008842.)

If P is the weight of the platinum, then if x is the temperature of the mixture, we have the equation—

$$P (95 - x) 0.0324 = 2 (x - 4).$$

To determine P we have—

(1) Volume of sphere at $95^\circ = \frac{4}{3} \pi r^3 = 4 \times 1.047 \times 125 = 523.5$ cubic centimetres.

(2) Its volume at $0^\circ = \frac{523.5}{1 + 95 \times 0.00008842} = 523.06$.

(3) Its weight $523.06 \times 22.07 = 11544$ kilogrammes.

Substituting this value for P in the above equation, $\therefore x = 18^\circ.3$.

6. 10 lbs. of iron at 100° are placed into 18 lbs. of water at 15° , and the temperature is constant at 20° . Find the specific heat of iron.

If x the specific heat of iron, then the thermal units in the water before mixing and afterwards, together with those of the iron, must be equal :

$$\therefore 18 \times 15 + x \times 10 \times 100 = 18 \times 20 + x \times 10 \times 20$$

$$x = .1125.$$

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Or thus : the water receives 18 (20 - 15) units, the iron gives up 10 (100 - 20) x . $\therefore 18 \times 45 = 800x$, or x as before.

7. Ten grammes of sodic chloride at 91° having been immersed in 125 grammes of oil of turpentine at 13° , the temperature of the mixture was 16° . Find the specific heat of sodic chloride, if that of turpentine = 0.428 .

Loss of chloride 10 (91 - 16) $x = 750x$ units.

Gain of turpentine $125 \times 3 = 375$.

$$x = \frac{375}{750} = \frac{1}{2} = 0.5.$$

Specific heat of salt = $0.5 \times 0.428 = .214$.

8. In order to determine the specific heat of a piece of metal, the following operations were carried out.

(a) The *water-equivalent* (see Art. 102, page 110) of the vessel and stirrer was determined. Both parts were made of brass, and weighed together 19 grammes. The specific heat of brass is = 0.094 . The equivalent therefore is $19 \times 0.094 = 1.8$ gramme.

(b) The equivalent of the thermometer was found. It was warmed to 45° , and plunged into a small vessel containing 20 grammes of water of the temperature of $16^{\circ}.25$. The temperature then rose to $17^{\circ}.10$. The equivalent of the thermometer therefore amounts to

$$20 \times \frac{17^{\circ}.10 - 16^{\circ}.25}{45 - 17.1} = 0.6 \text{ gramme.}$$

The equivalent of the solid parts of the calorimeter is therefore

$$1.8 + 0.6 = 2.4 \text{ grammes.}$$

(c) The body weighed 48.3 grammes.

The water weighed 74 grammes; adding

the water equivalent of the cali-

meter, viz. 2.4 grammes, the weight is 76.4 "

The temperature of the hot body was . $96^{\circ}.7$ "

The initial temperature of the water . $11^{\circ}.05$ "

The final temperature $16^{\circ}.74$ "

(The temperature of the room was 14° .)

Hence we find the specific heat of the body

$$= \frac{76.4}{48.3} \cdot \frac{16.74 - 11.05}{96.7 - 16.74} = 0.1125.$$

9. Still more accurate is the following determination of the specific heat of a sample of copper wire.

(a) The calorimeter and stirrer were made of brass, and weighed together 14.5 grammes, taking only those portions into

account which were afterwards immersed in or filled with water. Taking, again, the specific heat of brass as 0.094 , the equivalent of vessel and stirrer is—

$$14.5 \times 0.094 = 1.36 \text{ gramme.}$$

(b) In order to determine the equivalent of the thermometer, the calorimeter was filled with 35 grammes of water at $14^{\circ}.52$, the thermometer was heated to $34^{\circ}.2$ and quickly immersed in the water of the calorimeter, which rose to $14^{\circ}.63$. This gives the equivalent of the thermometer :

$$= \frac{(35 + 1.36) (14.63 - 14.52)}{34.2 - 14.63} = 0.2 \text{ gramme.}$$

(c) The copper wire was contained in a small test-tube during the experiment, of which the equivalent was determined in a similar manner, as for the thermometer, using in this determination

$$35 + 1.36 + 0.2 = 36.56 \text{ grammes}$$

as the quantity of water heated. The equivalent of the vessel was found to be 0.63 gramme.

(d) The temperature in the little vessel which contained the hot body was found by previous experiment to be $0^{\circ}.26$ higher than the maximum temperature which the calorimeter reached.

(e) The weight of the copper wire was . . . 20.5 grammes

 " " water in the calorimeter 1.5 "

The temperature of the hot body . . . $50^{\circ}.3$ "

The initial temperature of the calorimeter $14^{\circ}.4$ "

The final " " " " $17^{\circ}.94$ "

(The temperature of the air $16^{\circ}.2$.)

From these data we obtain the specific heat—

$$= \frac{36.56 (17.94 - 14.4) - (0.63 + 1.5) (50.3 - (17.94 + 0.26))}{20.5 (50.3 - (17.94 + 0.26))}$$

$$= 0.0927.$$

10. A constant source of heat is capable of heating 6 kilogrammes of water in two minutes from 10° to 30° . What time will be required to heat 200 kilogrammes of iron from 20° to 520° by the same source of heat?

(The specific heat of iron = 0.11379 .)

The time required will clearly be proportional to the thermal units required by each substance to heat it through the required range of temperature. Now the water requires 6 ($30 - 10$) units; the iron requires 200 ($520 - 20$) 0.11379 units.

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Hence—

$$6 \times 20 : 200 \times 500 \times 0.11379 :: 2 \text{ minutes} : x$$

$$x = 189.65 \text{ minutes} = 3\text{h. } 9.65 \text{ minutes.}$$

241. Pyrometric use of specific heat.—If the specific heat of a substance, and its variation with a rise of temperature be known, then the temperature to which a substance has been exposed can be calculated if a definite weight of the body be immersed in a given quantity of water, and the initial and final temperature of the water in the calorimeter be observed. The following examples will serve to show that the temperature of furnaces may be determined very accurately in this manner, if the experiments are conducted with sufficient care.

1. The specific heat of platinum between 0° and t° C. is

$$s = 0.03308 + 0.0000042 t.$$

If a sphere of platinum, which weighs 150 grammes, be placed in a furnace, of which the temperature is 1000° C., find the temperature to which 1 kilogramme of water at 10° will be raised, if the sphere be removed from the furnace and immediately thrown into the water.

The temperature of the water, introducing the numerical values into the equation which gives the specific heat by the method of mixtures, making the temperature the unknown quantity, will be—

$$t = \frac{1000 \times 1 \times 10 + 150 (0.03308 + 0.0000042 \times 1000) 1000}{1000 \times 1 + 150 (0.03308 + 0.0000042 \times 1000)}$$

$$= 15^\circ.505.$$

2. In the preceding problem the temperature of the furnace has been assumed as being given, and the temperature of the mixture was supposed to be unknown. The same equation will obviously give the temperature of the hot body, if the temperature of the mixture is observed and therefore known.

Thus, let the same sphere of platinum be removed from a hot furnace of unknown temperature and thrown into 1 kilogramme of water, of which the initial temperature was 15° C., while the temperature was $21^\circ.05$ after the platinum sphere was thrown into it. Then, calling t the unknown temperature :

$$150 (0.03308 + 0.0000042 t) (t - 21.05) = 1000 \times 6.05.$$

This leads to a quadratic equation, of which the two roots are

$$-8945.76, +1090.72,$$

of which only the latter value is admissible. Hence the temperature of the furnace was

$$1090.72.$$

242. **The two specific heats of air.**—It has already been pointed out in Art. 109, page 117, that the specific heat of a gas or vapour under a constant pressure is greater than under a constant volume. The ratio of these two specific heats of a gas—for example, air—is of great importance in several physical doctrines, and of the methods of determining this ratio that devised by *Clement* and *Desormes* will be explained in this article. Suppose, in *fig. 87*, a large globe *A* filled with dry air under the ordinary pressure of the atmosphere, having a volume *v* at the temperature *t*°. Let the globe be connected with a small pressure gauge *b*, and be capable of being opened and closed at will by the stopcock *a*, while *c* forms a connection with an air-pump. If while *a* is closed a small quantity of air be pumped out, and *c* be also closed afterwards, the pressure will fall from the atmospheric pressure *b* to *b* − *β*, as indicated by the gauge. If *s*₀ be the specific gravity of air at 0° or 760 millimetres pressure, and *γ* the coefficient of expansion, we shall have the following physical state of the air in the globe—

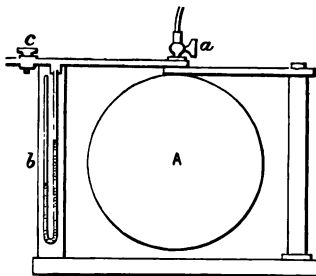


Fig. 87.

Volume.	Pressure.	Temperature.	Specific Gravity.
<i>v</i>	<i>b</i> − <i>β</i>	<i>t</i>	$s_0 \frac{b - \beta}{760} \cdot \frac{1}{1 + \gamma t}$

If now the stopcock *a* is quickly opened, air enters the globe, and the pressure of the air inside is again equal to the atmospheric pressure *b*. But the volume *v* which was previously in the interior of the globe is diminished in consequence of the increase of pressure, and becomes *v* − *v*. But as the compression produces a rise of temperature of *θ*₁°, we shall now have the following values for the above relations—

Volume.	Pressure.	Temperature.	Specific Gravity.
<i>v</i> − <i>v</i>	<i>b</i>	<i>t</i> + <i>θ</i> ₁	$s_0 \frac{b}{760} \cdot \frac{1}{1 + \gamma(t + \theta_1)}$

Let the stopcock *a* be again closed; the increase of temperature *θ*₁ will now disappear, and the pressure will fall from *b* to *b* − *β*₁. We shall therefore now have the following values for the above relations—

Volume.	Pressure.	Temperature.	Specific Gravity.
<i>v</i> − <i>v</i>	<i>b</i> − <i>β</i> ₁	<i>t</i>	$s_0 \frac{b - \beta_1}{760} \cdot \frac{1}{1 + \gamma t}$

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In all three states the weight of the gas was the same, hence the products of the volumes into the specific gravity must be the same; hence, leaving out the common factor $\frac{s_o}{760}$, we have the three equal quantities—

$$\frac{v(b-\beta)}{1+\gamma t} = (v-v) \frac{b}{1+\gamma(t+\theta_1)} = (v-v) \frac{b-\beta_1}{1-\gamma t},$$

from which θ_1 and v may be determined—

$$\theta_1 = \beta_1 \times \frac{1+\gamma t}{(b-\beta_1)\gamma}, \text{ and } \frac{v}{v} = \frac{\beta-\beta_1}{b-\beta_1}.$$

We know that if a certain weight of air p , having a volume v at the temperature t° , be heated through a small increase of temperature, then the increase in volume v will be $v_o \gamma \theta$, where v_o is the volume at 0° , and since $v = v_o(1+\gamma t)$, we conclude that the increase of temperature required for a definite increase in volume—

$$\theta = \frac{v}{v_o \gamma} = \frac{v}{v} \times \frac{1+\gamma t}{\gamma}.$$

Hence in this case, calling c the heat required for the weight p , when there is increase of volume, and c_1 that required without it—

$$\begin{aligned} \frac{\text{Specific heat under constant pressure}}{\text{Specific heat under constant volume}} &= \frac{c}{c_1} = \frac{\theta + \theta_1}{\theta_1} \\ &= \frac{\beta}{\beta - \beta_1} \end{aligned}$$

if the above values for θ and θ_1 are substituted.

In this manner by only observing on the gauge the changes of pressure β, β_1 , Clement obtained the ratio = 1.35. More recent observations by Masson and Dupré gave it as

$$1.41,$$

a value which, as will be seen further on, may be also obtained by various other physical methods.

243. **Latent heat.**—A. Let a solid substance, which weighs m kilogrammes, have the specific heat w_1 , temperature τ° , and let its fusing point be τ_f° . Let it be mixed with m kilogrammes of a substance, which has a specific heat = w , and a temperature t . The m kilogrammes become fused by the heat given up by the m kilogrammes, and when equilibrium is restored the whole has a temperature of τ° , while the specific heat of the fused substance in the liquid state is w . From these deter-

minations we may find the latent heat of fusion of the melted substance $= \lambda_1$.

The m kilogrammes have cooled from t° to τ° , and have given up $(t - \tau) m w$ units of heat. This heat has been used as follows :—

(a) M kilogrammes have been raised from τ to τ_f , and have required for this increase of temperature—

$$(\tau_f - \tau) M w_1 \text{ units.}$$

(b) The same weight has been fused, and required—

$$M \lambda \text{ units.}$$

(c) The same weight of the fused substance has been raised from τ_f to τ , and required—

$$M w (\tau - \tau_f) \text{ units.}$$

Hence we have the equation—

$$m w (t - \tau) = M w_1 (\tau_f - \tau) + M \lambda + M w (\tau - \tau_f).$$

From which we obtain—

$$\text{Latent heat of fusion} = \frac{m}{M} w (t - \tau) - w_1 (\tau_f - \tau) - w (\tau - \tau_f).$$

Any other unknown quantity may be clearly found from this equation if the others are given.

If the temperature is already at the fusing point, the term $w_1 (\tau_f - \tau)$ disappears. If the solid and liquid substance is the same, $w = w$, and the equation becomes—

$$\text{Latent heat} = \left[\frac{m}{M} (t - \tau) - (\tau - \tau_f) \right] w.$$

For water $w = 1$,

$$\tau_f = 0^\circ, \text{ hence latent heat} = \frac{m}{M} (t - \tau) - \tau.$$

Example.

The fusing point of lead is 330° ; its latent heat of fusion is 5.369. The specific heat of solid lead is 0.03144, that of molten lead 0.0402. Find (i) the weight of a solid piece of lead, at 300°C. , which was exactly fused by throwing it into 20 kilogrammes of liquid lead at 400° ; (ii) the weight of a solid piece of lead at 330°C. , under the same circumstances.

The above formula becomes, transformed—

$$\frac{M}{m} = \frac{w (t - \tau)}{\lambda_1 + w_1 (\tau_f - \tau) + w (\tau - \tau_f)}.$$

(I) In this case

$$\frac{M}{20} = \frac{0.0402 (400 - 330)}{5.369 + 0.03144 (330 - 300)} \quad (\text{because } \tau = \tau' = 330)$$

$$M = 8.916 \text{ kilogrammes.}$$

(II) Here $\tau = \tau_f = \tau = 330$

$$\therefore \frac{M}{20} = \frac{0.0402 (400 - 330)}{5.369}, \quad M = 10.42 \text{ kilogrammes.}$$

B. By the action of a constant source of heat a solid body of temperature t° and specific heat w_1 , is raised in z_1 minutes to the temperature t_1° , and further its temperature reaches the fusing point t_f° ; z_2 minutes now elapse before it is completely fused. The temperature then rises; the liquid, which has a specific heat of w , increases in z_3 minutes its temperature to t_3° , and finally its point of ebullition t_e° . In z_4 minutes it is completely evaporated. Find from this the latent heat of fusion and of evaporation, λ_f and λ_e .

If the substance has the mass m , then the units of heat produced by the constant source are—

$$\begin{aligned} &\text{In } z_1 \text{ minutes } m w_1 (t_1 - t) \therefore \text{ in 1 minute } \frac{m w_1 (t_1 - t)}{z_1} \\ &\text{In } z_3 \text{ minutes } m w (t_3 - t_2) \therefore \text{ in 1 minute } \frac{m w (t_3 - t_2)}{z_3} \end{aligned} \left. \begin{array}{l} \text{which} \\ \text{two are} \\ \text{equal.} \end{array} \right\}$$

Now during the z_2 minutes, when no sensible heat was produced, the heat being employed in fusing, the source gave off—

$$\frac{m w_1 (t_1 - t)}{z_1} z_2, \text{ or what is the same } \frac{m w (t_3 - t_2)}{z_3} z_2,$$

which is clearly $= m \lambda_f$ = the units required for fusing ;

$$\text{or } \lambda_f = \frac{z_2}{z_1} (t_1 - t) w_1, \text{ or } = \frac{z_2}{z_3} (t_3 - t_2) w.$$

Similarly during the z_4 minutes of vaporisation the heat given off was

$$\frac{m w_1 (t_1 - t)}{z_1} z_4, \text{ or } \frac{m w (t_3 - t_2)}{z_3} z_4,$$

$$\therefore \lambda_e = \frac{z_4}{z_1} w_1 (t_1 - t), \text{ or } \frac{z_4}{z_3} w (t_3 - t_2).$$

Example.

A piece of tin, specific heat $= 0.05628$, is heated from 15°C. to 75°C. in 14.216 minutes. When arrived at its fusing point, 230°C. , a full hour elapsed before it was melted completely. Find the latent heat of tin.

Here $w_1 = 0.05628$.

$$t = 15^\circ.$$

$$t_1 = 75^\circ.$$

$$Z_1 = 14.216 \text{ minutes.}$$

$$Z_2 = 60 \text{ minutes.}$$

$$\therefore \lambda_f = \frac{60}{14.216} 0.05628 (75 - 15) = 14.2523.$$

If these experiments are to be correct, the mass and specific heat of the vessel must be known, and then the formula becomes

$$\lambda_f = \frac{Z_2}{Z_1} (t_1 - t) (m w_1 + M w)$$

if M , w , are respectively mass and specific heat of the vessel.

Further examples:—

(1) 3 lbs. of ice mixed with 7 lbs. of water at 100° , give water at $46^\circ.2$. What heat has become latent in the melting of 1 lb. of ice?

The 7 lbs. of water have first 700 thermal units more than at 0° .

The 10 lbs. of water after melting have $10 \times 46.2 = 462$ thermal units.

The 3 lbs. of ice \therefore required $700 - 462 = 238$ units. \therefore each lb. $\frac{238}{3} = 79.3$, that is, as much as is required to heat 1 lb. of water to $79^\circ.3$.

$$\text{Or } 3x + 10 \times 46.2 = 7 \times 100 \\ x = 79.3.$$

(2) What will be the temperature of water if 3 lbs. of ice are placed in 4 lbs of boiling water?

$$4 \times 100 - 3 \times 80 = 7x \\ x = \frac{60}{7} = 22^\circ.86.$$

(3) How many pounds of snow must be mixed with 6 lbs. of water ($t = 95^\circ$) to obtain water at 10° C.?

$$(6 + x) 10 + x \times 80 = 6 \times 95, x = 5\frac{1}{2} \text{ lbs.}$$

(4) Ice at 0° is exposed to a constant source of heat.

It melts in 8 minutes; the water boils in 10 minutes more, and is boiled away in 54 minutes more, the temperature remaining constant during the time since it commenced boiling. Find from this experiment the latent heat of water and steam.

(5) A pound of steam at 100° C. is passed into 5.4 lbs. of water at 0° . What will be the temperature of the 6.4 lbs. of water?

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The steam contains 640 thermal units ; hence the temperature of the whole will be 100° .

(6) Four pounds of steam at 100° are carried into 60 lbs. of water at 0° . What will be the temperature of the whole after condensation ? What would have been the temperature if the water had already been at 16° C.?

(a) 4×640 units are distributed over 64 lbs. Each pound receives $\therefore \frac{2560}{64} = 40$, and is therefore at 40° . Or, if x be the temperature, $60 \times x = 4(640 - x)$, $x = 40$.

(β) $60(x - 16) = 4(640 - x)$, $x = 55^{\circ}$.

7. How many pounds of steam at 121° C. are required to heat 300 lbs. of water from 11° to 28° ?

The increase of temperature being 17° , the units required are $17 \times 300 = 5100$.

But 1 lb. of steam at 121° , condensed into water at 28° , gives up $\underbrace{121 + 519 - 28}$ units,

$$= 612, \therefore \frac{5100}{612} = 8\frac{1}{3} \text{ lbs. are required.}$$

Or thus : $300(28 - 11) = x(640 - 28)$, x as before.

8. A piece of tin is melted. What would be the temperature of the molten mass, if the heat required for the change of state had become all sensible ?

Latent heat of tin = $14\cdot3$.

Specific heat of tin = $0\cdot0562$.

Temperature of melting point 235° .

The latent heat being $14\cdot3$, means that $14\cdot3$ times the quantity of heat becomes latent than would be required to heat an equal weight of water through 1° . But since the specific heat of tin is $0\cdot0562$, the heat which becomes latent would raise the temperature of the same mass of tin by $\frac{14\cdot3}{0\cdot0562}$ degrees = 255 .

Hence if no heat became latent, the temperature of the mass would be $235 + 255 = 490^{\circ}$ C.

9. How many pounds of ether could be raised from 0° to the boiling point ($35^{\circ}\cdot6$) by the heat required for vaporisation of 1 lb. of it ? (Specific heat of ether = $\cdot55$. Latent heat $91\cdot1$.)

To raise x lbs. of ether from 0° to $35^{\circ}\cdot6$, the thermal units required are $x \times \cdot55 \times 35\cdot6$, which must clearly be derived from the latent heat of the 1 lb., viz. $91\cdot1$,

$$\therefore x \times \cdot55 \times 35\cdot6 = 91\cdot1, x = 4\cdot65 \text{ lbs.}$$

10. Into 20 litres of water at 80° a sphere of ice of 144 millimetres radius is thrown. What will be the temperature of the whole after the ice is fused? (Latent heat $79\cdot25$.) (Specific gravity (D) of ice = $\cdot91$.)

The weight of the sphere is $w = v \cdot D$.

$$w = \frac{4}{3} \pi r^3 D = \frac{4}{3} \times \frac{22}{7} \times .91 \times (1\cdot44 \text{ decim.})^3 = 11\cdot38 \text{ kilos.}$$

The required temperature being x° , the ice requires for fusion and for raising it to x°

$$\begin{aligned} & 11\cdot38 (79\cdot25 + x) \text{ units ;} \\ & \text{the water loses } 20 (80 - x) \\ \therefore 20 (80 - x) &= 11\cdot38 (79\cdot25) + 11\cdot38 x \\ 20 \times 80 - 11\cdot38 \times 79\cdot25 &= 31\cdot38 x \\ x &= 22^{\circ}\cdot2. \end{aligned}$$

11. How many kilogrammes of steam will raise 20 kilogrammes of water from 0° to 90° ? (Latent heat of steam 540 .)

$$\begin{aligned} \text{Let } x &= \text{number of kilogrammes required,} \\ 540 x &= \text{units of heat given off in condensing,} \\ \text{and cooling to } 90^{\circ} &\text{ it gives off further } 10 x \\ \therefore 550 x &= \text{units given off by steam,} \\ \text{and } 20 \times 90 &= \text{heat taken up by the water} \\ \therefore 550 x &= 1800 \\ x &= 3\cdot372 \text{ kilogrammes.} \end{aligned}$$

12. (a) 5 oz. of water at 40° C. are poured over 1 oz. of ice. What is the temperature of the mixture?

$$\frac{5 \times 40 - 80}{6} = 20^{\circ} \text{ C.}$$

(b) If the whole of this quantity of water be boiled away, and the steam directed into a pound of water at 0° , what temperature will the water have, and how much of it will be left after the experiment is completed?

We have 6 oz. of water.

1 oz. in boiling away heats $5\frac{1}{2}$ oz. to 100° (i.e. gives off 550°)
 \therefore 6 oz. in boiling away heat 33 oz. to 100° (i.e. give off 3300°).
 But here only 16 oz. are presented. \therefore only 1600 units are required for raising the temperature of the pound of water to 100° ,
 \therefore 1700 units are at our disposal for converting some of the boiling water into steam; now 550 units will boil away 1 oz.

$$\therefore \frac{1700}{550} = \frac{34}{11} = 3\frac{1}{11} \text{ oz. will be boiled away, and } 6 + 16 - 3\frac{1}{11} = 18\frac{10}{11} \text{ oz. will be left.}$$

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244. **Mixtures of vapours and gases.**—Let, 1st, v be a volume of *dry* air, at pressure H , which becomes saturated with vapour. Find its new volume, the temperature and pressure remaining the same.

Let F be the tension of the saturated vapour, then $H - F$ must be the tension of the air in the mixture.

But $vH = v'(H - F)$, v' being the new volume

$$\therefore v' = \frac{vH}{H - F}.$$

2. Let v = volume of *saturated* air at pressure H and temperature t . Find v' at any other pressure H' , and temperature t' , when it is also saturated.

Let f, f' be the tensions at t, t' of saturated vapour. Then the air in both mixtures has respectively the tensions $H - f, H' - f'$, and if the temperature were unchanged $\therefore v(H - f) = v'(H' - f')$,

but the volumes v, v' are as $(1 + \alpha t) : (1 + \alpha t')$

$$\therefore v'(1 + \alpha t) = v(1 + \alpha t') \therefore v(1 + \alpha t')(H - f) = v'(1 + \alpha t)(H' - f')$$

$$\therefore v' = \frac{v \cdot 1 + \alpha t' \cdot H - f}{(1 + \alpha t) \cdot (H' - f')}$$

3. Find the weight P of a volume of air v , saturated with aqueous vapour at the temperature t , and pressure H . Let F be the tension at t , then the air has the tension $H - F$, or we have to find :

1. The weight of volume v of air at t under pressure $H - F$.

2. The weight of volume v of vapour at t under pressure F .

1st. One litre of air weighs 1·293 grammes at 0° degrees and 760 millimetres.

$$\therefore v \text{ litres weigh } v \times 1\cdot293 \text{ grammes ;}$$

$$\text{weight at } t = \frac{v \times 1\cdot293}{1 + \cdot003665 t},$$

and at pressure $H - F$;

$$\text{weight} = \frac{v \times 1\cdot293 (H - F)}{760 (1 + \cdot003665 t)}.$$

2nd. Since density of steam = $\frac{5}{8}$ of air, we have for the weight of the vapour :

$$\begin{aligned} \therefore \text{weight of whole} &= \frac{v \times 1\cdot293 \times F \times 5}{760 (1 + \cdot003665 t) \cdot 8} \\ &+ \frac{v \times 1\cdot293 (H - F)}{760 (1 + \cdot003665 t)} + \frac{v \times 1\cdot293 F \times 5}{760 (1 + \cdot003665 t) \cdot 8} \\ &= \frac{v \times 1\cdot293}{(1 + \alpha t) 760} (H - \frac{3}{8} F). \end{aligned}$$

245. Problems on the tension and density of vapours.

—1. Steam at 100° and 760 millimetres pressure has 1700 times the volume of water at 0° which produced it; atmospheric air at 0° and 760 millimetres pressure has 773 times the volume of an equal weight of water at 0° . Compare from this the density of steam and air at 100° C. and 760 millimetres pressure.

$$\text{A unit volume of air at } 0^{\circ} \text{ is at } 100^{\circ} = 1 + \frac{100}{273} = \frac{373}{273};$$

$$\text{its density at } 0^{\circ} \text{ being } \frac{1}{773}, \text{ it is at } 100^{\circ} = \frac{273}{373 \cdot 773} = \frac{1}{1052}.$$

$$\text{Hence steam at } 100^{\circ} \text{ degrees : air at } 100^{\circ} :: \frac{1}{1700} : \frac{1}{1052} :: 62 : 1 \\ :: 5 : 8,$$

a ratio which is also adopted for other temperatures (and tensions) common to the steam and the air.

2. The tension of aqueous vapour at 0° is 5 millimetres. What is its density?

Since air under a pressure of 5 millimetres has a density of $\frac{5}{760}$ of the air under the pressure of 760 millimetres, its density, compared with water, would be $\frac{1}{773} \cdot \frac{5}{760}$.

But density of air : density of steam : 8 : 5

$$\therefore \text{density of steam at 5 millimetres} = \frac{5}{8} \cdot \frac{1}{773} \cdot \frac{5}{760} = .0000054$$

3. What is the density of saturated steam of 40° C. ? (Tension = 53 millimetres.)

$$1 \text{ volume of air at } 0^{\circ} \text{ is } 1 + \frac{40}{273} = \frac{313}{273} \text{ at } 40^{\circ}$$

$$\therefore \text{its density} = \frac{273}{313 \cdot 773},$$

$$\text{and under a pressure of 53 millimetres} = \frac{53 \times 273}{760 \times 313 \times 773}$$

$$\therefore \text{density of steam} = 5 \times \frac{53}{760} \times \frac{273}{313 \times 773} = \frac{1}{20000} \text{ nearly.}$$

4. What is the weight of a cubic foot of aqueous vapour at 50° C. ?

(1 cubic foot of air at 0° , 760 millimetres, weighs 567.85 grains.)
(Tension of vapour at 50° = 88.742 millimetres.)

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1 cubic foot of air at 88.742 millimetres pressure, and 50° C., weighs—

$$\frac{567.85}{1 + 0.003665 \times 50} \times \frac{88.742}{760} \text{ grains,}$$

∴ the aqueous vapour weighs :

$$\frac{5}{8} \times \frac{567.85}{1 + 0.003665 \times 50} \times \frac{88.742}{760} \text{ grains.}$$

5. Find the weight of saturated vapour contained in a cubic foot of air at 25° C.

$$\left(\begin{array}{l} \text{Tension at } 25^\circ \text{ C.} = 23.1 \text{ millimetres.} \\ \text{1 cubic foot of water weighs } 62.3 \text{ lbs.} \end{array} \right)$$

The weight is—

$$\frac{5}{8} \times \frac{273}{273 + 25} \times \frac{23.1}{760} \times \frac{1}{773} \times 62.3$$

6. What is the tension of aqueous vapour, removed from the liquid, if heated from 100° to 121°, the volume remaining constant?

$$\begin{aligned} \text{The tension increases in the ratio } 1 + \frac{100}{273} : 1 + \frac{121}{273} \\ \therefore 373 : 394 ; \end{aligned}$$

and since the tension at 100° = 760 millimetres,

$$\therefore 273 : 394 :: 760 : x = 803 \text{ millimetres.}$$

7. At 121° C. the tension of vapour is two atmospheres. Find at this temperature the density of saturated steam.

The density of air at 121° at 1 pressure of the atmosphere is

$$\frac{273}{394} \times \frac{1}{773} ;$$

at 2 pressures it is $\frac{273}{394} \times \frac{2}{773}$, hence the density of the vapour is

$$\frac{5}{8} \times \frac{273}{394} \times \frac{2}{773} = \frac{1}{889} \text{ of the density of water.}$$

8. What is the weight of a cubic foot of saturated steam at 5 pressures of the atmosphere, and a temperature of 153° C.?

$$\text{Density} = \frac{5}{8} \times \frac{5}{773} \times \frac{273}{426} = \frac{1}{384} \text{ of that of water,}$$

$$\therefore \text{weight} = \frac{1}{384} \times 62.3 \times 7000 \text{ grains.}$$

9. At a temperature of 25° the dewpoint is found to be 12°. What is the weight of the vapour in one cubic foot of air?

(Tension at $12^{\circ} = 10.707$ millimetres.)

$$\text{Weight} = \frac{5}{8} \times 62.3 \times \frac{1}{773} \times \frac{10.707}{760} \times \frac{273}{298} \text{ lbs.}$$

10. A Daniell's hygrometer gives a dewpoint of 13° , while the external reading is 24° C. How many per cent. of vapour are still wanting for complete saturation?

$$\left(\begin{array}{l} \text{Tension at } 13^{\circ} = 11.4 \text{ millimetres.} \\ \text{,, } 24^{\circ} = 21.8 \text{ ,,} \end{array} \right)$$

The tensions are proportional to the density (and weight).

Hence the vapour present is $\frac{11.4}{21.8}$ of the total quantity which the air is capable of containing, until it becomes saturated at 24° .

The percentage present is $\therefore \frac{11.4}{21.8} \times 100 = 52$,

and 48 per cent. are wanting for saturation.

11. What quantity of rain can fall from a volume of air, covering a square mile, and being 1000 feet high, which is at 20° C., is saturated with vapour, but is suddenly cooled by a N.E. wind to 11° C.?

$$\left(\begin{array}{l} \text{Tension at } 20^{\circ} \text{ C.} = 17.314. \\ \text{,, } 11^{\circ} \text{ C.} = 10.074. \end{array} \right)$$

We have 1000×5280 cubic feet of air.

The weight of saturated vapour at 20° C. is

$$\frac{5}{8} \times 62.3 \times \frac{1}{773} + \frac{17.314}{760} \times \frac{273}{293}$$

in pounds per cubic foot.

Similarly the weight of saturated vapour at 11° C. is

$$\frac{5}{8} \times 62.3 \times \frac{1}{773} + \frac{10.074}{760} \times \frac{273}{284}$$

The difference per cubic foot is precipitated. Multiplying this difference by 1000×5280 we find the total precipitation in pounds.

12. A certain quantity of dry air weighs 5.2 grammes, at 0° and 750 millimetres pressure. It is heated to 20° C., and then allowed to become saturated with aqueous vapour. The pressure is found to be 770 millimetres. What will be its volume?

(1 litre of dry air at $\frac{0}{760}$ weighs 1.3 grains. Tension of vapour at $30^{\circ} = 31.5$ millimetres.)

The volume at $0^{\circ} = \frac{5.2}{1.3} = 4$ litres.

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At $30^{\circ} = 4 (1 + 30 \times .003665)$,

and at the pressure 770 millimetres $= 4 (1 + 30 \times .003665) \frac{760}{770}$.

But the pressure of the air alone is $770 - 31.5$.

\therefore the volume $= 4 (1 + 20 \times .003665) \frac{760}{770 - 31.5} = 4.54$ litres.

BOOK THE SECOND.

THE PROPAGATION OF HEAT, AND ITS NATURE.

CHAPTER XII.

CONDUCTION.

246. **Conductors.**—When heat is imparted to one part of any mass of matter, the temperature of that part is raised above that of the other parts. This inequality, however, is only temporary. The heat gradually diffuses itself from particle to particle throughout the volume of the body, until a perfect equilibrium of temperature has been established. Different bodies exhibit a different facility in this gradual transmission of heat. In some it passes more rapidly from the hotter to the colder parts than in others. Those bodies in which it passes easily and rapidly are *good conductors*. Those in which the temperature is equalised slowly are *bad conductors*.

Let A B (*fig. 88*) be a bar of metal having a large cavity formed at its extremity A, and having a series of small cavities formed at equal distances throughout its length at T_1, T_2, T_3 , &c.

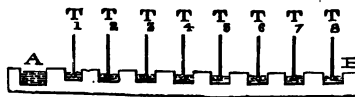


Fig. 88.

Let the bulbs of a series of thermometers be immersed in mercury in these cavities severally. These thermometers will all indicate the same temperature, being that of the bar A B.

Let the large cavity A, at the end of the bar, be filled with mercury at a high temperature, 200° , for example.

After the lapse of some minutes the thermometer T_1 will begin to rise; after another interval the thermometer T_2 will begin to be affected; and the others, T_3, T_4 , &c., will be successively affected in the same way; but the thermometer T_1 , by continuing to

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rise, will indicate a higher temperature than t_2 , and t_2 a higher temperature than t_3 , and so on. After the lapse of a considerable time, however, the thermometer t_1 will become stationary. Soon afterwards t_2 , having risen to the same point, will also become stationary; and in the same manner all the others, having successively risen to the same point, will become stationary.

If several bars of different substances of equal dimensions be submitted to the same process, the thermometers will be more or less rapidly affected, according as the bars are good or bad conductors.

Another form of apparatus for a like purpose is shown in *fig. 89*. A series of thermometers, as before, are inserted in

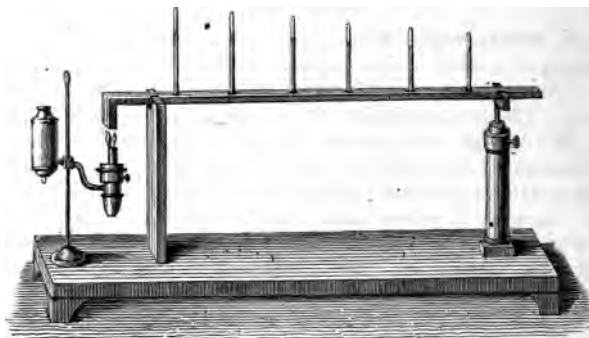


Fig. 89.

cavities filled with mercury in a bar supported horizontally, one end of which is heated by a lamp. The progressive propagation of the heat is indicated by the gradual diminution in the lengths of the mercurial columns.

An apparatus by which the unequal conductivity of different bodies is exhibited in a striking manner is represented in *fig. 90*. A series of rods of equal length and thickness are inserted at the same depth in the side of a rectangular vessel, passing across the interior of the vessel to the opposite side. The rods, which are silver, copper, iron, glass, porcelain, wood, &c., are previously covered with a thin coating of wax, or any other substance which will melt at a low temperature. Boiling water or heated mercury is poured into the vessel, and imparts heat to those parts of the rods which extend across it. It is found that the heat, as it passes by conduction along the rods, melts the wax from their surface.

Those which are composed of the best conductors—silver, for example—will melt off the wax most rapidly; the less perfect conductors less rapidly; and on the rods composed of the most imperfectly conducting materials, such as glass or porcelain, the wax will not be melted beyond a very small distance from the point where the rod enters the vessel.

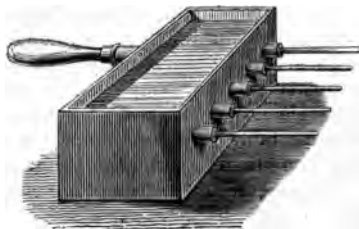


Fig. 90.

247. Table of conducting powers.—By

experiments conducted in this manner it was found that the conducting powers of the subjoined substances are in the ratio here expressed, that of gold being 100 :—

Gold	100·00	Tin	30·38
Platinum	98·10	Lead	17·96
Silver	97·30	Marble	2·34
Copper	89·82	Porcelain	1·22
Iron	37·41	Brick earth	1·13
Zinc	36·37		

It is evident, therefore, that metals are the best conductors of heat, and it was thought also that in general the conducting power increases with the specific gravity, as will appear by comparing the preceding numbers with those given in the table of specific gravity. (See *HYDROSTATICS*, p. 90.) It was also found that among woods, with some exceptions, the conducting power increases with the density. The conducting power of nut wood, however, was found greater than that of oak.

Bodies of a porous, soft, or spongy texture, and more especially those of a fibrous nature, such as wool, feathers, fur, hair, &c., are the worst conductors of heat.

248. More recent researches on conduction.—It will appear, on more careful consideration, that in experiments carried out in the manner described various other physical characteristics of bodies ought to be considered before we can definitely pronounce, from the results of these experiments, on their relative conducting power. Thus, if we suppose two of the bars in the apparatus *fig. 90* to have the same conducting power, but to differ considerably in their specific heat, it will at once appear that the bar which has the less specific heat will exhibit very soon a more rapid increase of

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temperature when exposed to the same source of heat than the bar of which the specific heat is greater. Hence more careful experiments have been made in recent times for determining the relative conducting power of substances.

Messrs. *Franz* and *Wiedemann* adopted the method of which *fig. 89* gives a general representation, but, instead of using thermometers, they employed a suitable modification of the thermo-electric pile (see *ELECTRICITY*, Art. 381, p. 239). The following table, which gives some of their results, exhibits at the same time a very striking analogy between the conductivity of metals for heat and their conductivity for electricity:—

Conductivity.				Conductivity.			
Substance.	For Heat.	For Electricity.		Substance.	For Heat.	For Electricity.	
Silver . .	100 . .	100		Iron . .	12 . .	13	
Copper . .	74 . .	73		Lead . .	9 . .	11	
Gold . .	53 . .	59		Platinum .	8 . .	10	
Brass . .	24 . .	22		German silver	6 . .	6	
Tin . .	15 . .	23		Bismuth .	2 . .	2	

It will be seen, by comparing this table with that in the preceding article, that the conductivity is by no means connected with the relative specific gravity of the metals, and that even among the metals there exist great differences in their conducting power. Thus, the conductive power of silver being 100, that of German silver is only 6, and we may easily convince ourselves of this difference in a very simple way, by plunging two spoons, one of German silver and the other of pure silver, into the same vessel of hot water. After a little time we shall find the free end of the silver spoon much hotter than that of its neighbour.

The table exhibits a very important connexion between heat and electricity. We know that heat and electricity are interdependent, and that they are mutually convertible, but as yet we know very little as to the precise form of the conversion. We have every reason to conclude, that the physical manifestations which we ascribe to heat and to electricity are both modes of molecular motion, and we know experimentally that from electricity we can obtain heat, and from heat, as in the case of the thermo-electric pile, we can obtain electricity. But although we have arrived on the whole at very tolerably clear ideas of the character of the kind of motion called heat, no clear perception whatever exists as yet as to the precise nature of the change which this motion must undergo in order to appear as electricity. The facts proved by *Franz* and *Wiedemann* show what the late

Professor *Forbes* has already noticed previously, that the good conductor of heat is the good conductor of electricity, and the bad conductor of heat is the bad conductor of electricity. Thus we may infer that the same physical quality which resists the transmission of heat, interferes also in a proportional degree with the transmission of electricity. This indicates a relation on which no doubt light will be thrown by further investigations.

249. **Variations of conductivity in the same body.**—The same substance may possess different powers of conduction in different directions. Many crystals are so built that the motion of heat runs with greater facility along certain lines of molecules than along others. A crystal of quartz (rock-crystal) forms a six-sided pillar terminated at either end, when complete, by a six-sided pyramid. M. de *Senarmont* has shown that heat travels with greater facility along the axis of this crystal than across it, by employing a method similar to that explained in Art. 246. Let

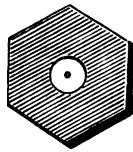


Fig. 91.

fig. 91 represent a plate of quartz cut perpendicularly to the axis of the crystal, and *fig. 92* a plate cut parallel to it. The plates are first coated with a layer of white wax, laid on with a camel's-hair pencil. They are pierced at the centre, and into the hole is inserted a small sewing-needle, which is at both ends, by means of a suitable arrangement, connected with an electric current. When the current passes the needle is heated and the heat is propagated in all directions. The wax melts around the place where the heat is applied; and on the plate in *fig. 91*, which is cut perpendicularly to the axis of the quartz, the figure of the melted wax is a perfect circle. The heat has travelled with the same rapidity all round, and melted the wax to the same distance in all directions. But if the same experiment be made with the other plate, *fig. 92*, this figure is no longer a circle: the heat travels more speedily along the axis than across it, and hence the wax figure is an ellipse, instead of a circle. This relation between the two directions is, however, not the same in crystals of other substances. Iceland spar conducts also better along the crystallographic axis than

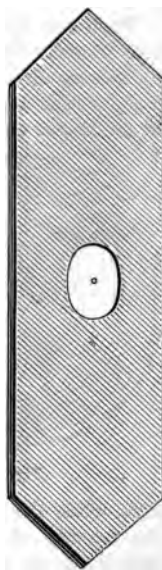


Fig. 92.

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at right angles to it, but a crystal of tourmaline conducts best at right angles to its axis. Bismuth, which cleaves with great facility in a certain direction, conducts both heat and electricity better along the planes of cleavage than across them.

250. **Conductivity of wood.**—Wood is a striking example of this difference of conductivity in different directions. *De la Rive* and *De Candolle* instituted many years ago an inquiry into the conductive power of wood, and in the case of five specimens examined, they established the fact that the velocity of transmission was greater along the fibre than across it. The experiments were conducted in the manner described in Art. 246, of which *fig. 89* gives a representation. A bar of the substance was taken, one end of which was brought into contact with a source of heat, and allowed to remain there until a state of equilibrium was assumed. The temperatures attained by the bar, at various distances from its heated end, were ascertained by means of thermometers fitting into cavities made to receive them; from these data, with the aid of a well-known formula (see further on) the conductivity of the wood was determined.

Professor *Tyndall* made a number of very careful determinations in order to determine the velocity of calorific transmission in different directions through wood. There are in wood three lines, at right angles to each other, which the mere inspection of the substance enables us to fix upon as the necessary resultants



Fig. 93.

of structural arrangement due to molecular action: the first line is parallel to the fibre; the second is perpendicular to it and to the ligneous layers which indicate the annual growth of the tree, as *m n* in *fig. 93*; while the third is perpendicular to the fibre and parallel, or rather tangential, to the layers, as *a b*, in the figure. From each of a number of trees a cube was cut, two of the faces being parallel to the ligneous layers, two perpendicular to them, while the remaining two were perpendicular to the fibre.

The velocity of calorific transmission was examined in these three directions, with the following results, in which the numbers give the angular deflections of the galvanometer connected with the thermo-pile used in all the experiments:—

Description of Wood	DEFLECTIONS		
	I. Parallel to fibre	II. Perpendicular to fibre and parallel to ligneous layers, <i>ab.</i>	III. Perpendicular to fibre and to ligneous layers, <i>mn.</i>
1. American birch . . .	35	9°0	11°0
2. Oak	34	9°5	11°0
3. Beech	33	8°8	10°8
4. Coromandel wood . . .	33	9°8	12°3
5. Bird's-eye maple . . .	31	11°0	12°0
6. Lance-wood	31	10°6	12°1
7. Box-wood	31	9°9	12°0
8. Teak-wood	31	9°9	12°4
9. Rosewood	31	10°4	12°6
10. Peruvian-wood . . .	30	10°7	11°7
11. Greenheart	29	11°4	12°6
12. Walnut	28	11°0	13°0
13. Drooping ash	28	11°0	12°0
14. Cocoa-wood	28	11°9	13°6
15. Sandal-wood	28	10°0	11°7
16. Tulip-wood	28	11°0	12°1
17. Camphor-wood	28	8°6	10°0
18. Olive-tree	28	10°5	13°2
19. Ash	27	9°5	11°5
20. Black oak	27	8°0	9°4
21. Appletree	26	10°0	12°5
22. Iron-wood	26	10°2	12°4
23. Chestnut	26	10°1	11°5
24. Sycamore	26	10°6	12°2
25. Honduras mahogany . .	25	9°0	10°0
26. Brazil-wood	25	11°9	13°9
27. Yew	24	11°0	12°0
28. Elm	24	10°0	11°5
29. Plane-tree	24	10°0	12°0
30. Portugal laurel	24	10°0	11°5
31. Spanish mahogany . . .	23	11°5	12°5
32. Scotch fir	22	10°0	12°0

This table furnishes a corroboration of the result arrived at by De la Rive and De Candolle regarding the superior conductivity of the wood in the direction of the fibre. It shows also how little mere density affects the velocity of transmission. Neither law nor general rule connects one with the other.

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American birch, a comparatively light wood, possesses a higher conductive power than any other in the list. Iron-wood, on the contrary, with a specific gravity of 1.426, stands low. Again, oak and Coromandel-wood—the latter so hard and dense that it is used for sharp war-instruments by savage tribes—stand near the head of the list, while Scotch fir and other light woods stand low.

The second and third columns of the table show clearly that in every instance the velocity of propagation is greatest in a direction perpendicular to the ligneous layers. Professor Tyndall enounces thus the law of molecular action as regards the transmission of heat through wood: 'At all points, not situate in the centre of the tree, wood possesses three unequal axes of caloric conduction, which are at right angles to each other. The first and principal axis is parallel to the fibre of the wood; the second and intermediate axis is perpendicular to the fibre and to the ligneous layers; while the third and least axis is perpendicular to the fibre and parallel to the layers.'

The difference in the conductive power of wood in these different directions is not without some influence, for the feeble conducting power in a lateral direction must tend to preserve within a tree the warmth which it acquires from the soil. In virtue of this property also a tree is able to resist sudden changes of temperature which would probably be prejudicial to it: it resists alike the sudden abstraction of heat from within and the accession of it from without. Nature has gone farther, and clothes the tree with a sheathing of worse-conducting material than the wood itself, even in its worst direction. The following are the deflections, observed by Professor Tyndall, when a number of cubes of bark, of the same size as the cubes of wood, were submitted to experiment:—

	Deflection.	Corresponding deflection by the wood.
Beech-tree bark . . .	7°	10.8°
Oak-tree bark . . .	7	11.0
Elm-tree bark . . .	7	11.5
Pine-tree bark . . .	7	12.0

In these cases the direction of the transmission was from the interior of the bark outwards.

254 Conductivity of organic substances.—The following numbers express the conductive powers of a few organic structures:—

Tooth of walrus	16
Tusk of East Indian elephant	17
Whalebone	9
Rhinoceros horn	9
Cow's horn	9

In general, the conductivity of organic substances is inconsiderable, and those used in the construction of tissues are such as are best suited to resist sudden changes of temperature. This fact is further illustrated by the following experiments. A cube of each of the substances named was submitted to an examination by the thermopile as to its conducting power, and while the deflection produced by a cube of quartz was 90° , it was 0° for sealing wax, sole leather, bees' wax, glue, gutta-percha, india-rubber, filbert-kernel, almond-kernel, boiled ham-muscle, raw veal-muscle. Thus all these animal and vegetable productions were demonstrated to be extremely impervious for the conduction of heat. Organic substances are, indeed, all bad conductors.

252. **Rumford's experiments.**—Rumford made an elaborate series of experiments on the conductivity of the substances used in clothing. His method was this:—A mercurial thermometer was suspended in the axis of a cylindrical glass tube, ending with a globe, in such a manner that the centre of the bulb of the thermometer occupied the centre of the globe. The space between the internal surface of the globe and the bulb was filled with the substance whose conductive power was to be determined. The instrument was heated in boiling water, and afterwards plunged into a freezing mixture of pounded ice and salt, the times of cooling down through 135° F. being noted. These times are given in the following table:—

<i>Surrounded with—</i>	<i>Seconds.</i>
Twisted silk	917
Fine lint	1032
Cotton wool	1046
Sheep's wool	1118
Taffety	1160
Raw silk	1204
Beaver's fur	1296
Eiderdown	1305
Hare's fur	1312
Wood ashes	927
Charcoal	937
Lampblack	1117

253. Influence of mechanical state on conductivity.—

The different result obtained in the above table, when twisted and raw silk was used, indicates a difference in the conducting power of the same substance when in different mechanical states. This principle holds good in many other cases. Pure silica, in the state of hard rock crystal, is a better conductor than bismuth or lead; but if the crystal be reduced to powder, the propagation of heat through that powder is exceedingly slow. Through transparent rock salt heat is abundantly conducted, through common table salt very feebly. If some asbestos, a substance composed of certain silicates in a fibrous condition, be placed on the hand, and on the asbestos a red-hot iron ball, the ball can be supported without inconvenience. The asbestos intercepts the heat. Heat being motion, anything which disturbs the continuity of the chain of molecules along which the motion is conveyed must retard the transmission; hence division of a substance interferes with conductivity. In the case of the asbestos, the fibres of the silicates are separated from each other by spaces of air; to propagate itself, therefore, the motion has to pass from the solid to the air, a very light body, and again from the air to the solid, a comparatively heavy body; and it is easy to see that the transmission of motion through this composite texture must be very imperfect. In the case of an animal's fur this is more especially the case, for here not only do spaces of air intervene between the hairs, but the hairs themselves, unlike the fibres of the asbestos, are very bad conductors. Many other instances, illustrative of the same principle, are mentioned further on.

254. Transmission of heat along bars.—If a metallic bar is heated at one end by a constant source of heat, for example, as in *fig. 89*, Art. 246, the whole bar will become gradually hotter, but its temperature at the opposite extremity will never be so high as at the end directly exposed to the source of heat. After a certain time the temperature at each point along the bar becomes stationary; no further rise takes place, but a state of thermal equilibrium is reached, and the temperature is found to be decreasing as we measure it along the bar from the heated end to the opposite one.

If we imagine the bar to be divided into an infinite number of thin slices by cross sections, then the thermal equilibrium will exist for each slice, if it loses at any instant of time precisely as much heat as it receives from the source of heat. But each slice does not only give up heat to the next one in succession, but loses also heat to the surrounding bodies; hence each slice

receives less heat than the preceding one, and the temperature of every slice must thus decrease the further away it is from the source of the heat. This decrease of temperature is indicated in *fig. 89*, Art. 246, by the differences in the height of the mercury contained in the successive thermometers. Despretz, who was the first to employ this method, found that it took from two to three hours before the bar assumed a state of equilibrium. A bar of copper gave the following results :—

<i>Distance from the source of heat.</i>	<i>Excess of temperature above that of the surrounding air.</i>
Millimetres.	°
100	66·4
200	46·3
300	32·6
400	24·5
500	18·6
600	16·2

In looking more closely at the right side of this little table we shall find that the excess of temperature of each successive thermometer is on the average 1·325 times less than the excess of the thermometer which precedes it ; in other words, while the distance increases in an arithmetical series, the excess decreases in a geometrical series, of which in this case $\frac{1}{1\frac{1}{325}}$ is the common ratio. The same law does not, however, hold strictly good in bad conductors.

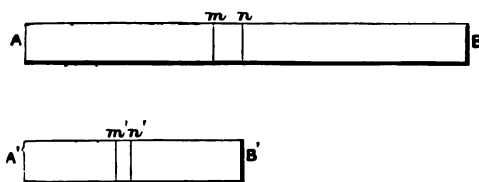
Let us now suppose that of some metal the conductivity is so much less than that of copper that if two bars, one of the metal and the other of copper, be both treated experimentally exactly in the manner described in Art. 246, the excess of temperature shown by the successive thermometers in the metal bar above the temperature of the air is just half of what it is in the copper bar, both bars being of the same dimensions. Then clearly the excess of temperature in any slice of the weak conductor would be just the same as in a slice of the copper bar, which is twice as far from the source of heat ; in other words, if two bars of these metals were exposed to the same source of heat, both bars being of the same thickness, but the copper bar twice as long as the other, both bars would have the same temperature at their free ends.

Let, in *fig. 94*, AB represent the bar of copper, and A'B' the bar of metal which is the inferior conductor assumed above, A'B' having half the length of AB. Then, from what has been

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stated just now, the free ends B and B' will be at the same temperature, if A and A' are heated by the same constant source of heat, and thermal equilibrium is arrived at. Similarly, if the slice n' is half as far from B' as n is from B , there will be the same temperature indicated at n' as at n . But since nB is twice $n'B'$, the portion nB must in the same time give up twice as much heat to the surrounding neighbourhood as the portion $n'B'$ of the other bar; hence twice as much heat must reach the portion nB in the same time, as compared with that which reaches $n'B'$.

Fig. 94.



Further, if mn is twice $m'n'$, the slices m and m' will be at the same temperature; and if through the layer mn the same quantity of heat would flow which flows through the layer $m'n'$, then the conductivity of copper would be clearly twice that of the other metal. But through mn passes in the same time twice as much heat as flows through $m'n'$, because the portion nB loses in the same time twice as much as $n'B'$ loses; hence in our case the conductivity of the copper is four times greater than that of the other bar.

From these considerations we may conclude generally that in bars of different metals their relative conductivity is to one another in the ratio of the squares of the distances between the source of heat and the points where an equal excess of temperature prevails, all other circumstances being the same.

This law is, however, only approximately correct, and does not appear to hold good for inferior conductors.

255. Comparison of the conducting power of two rods.—A method which leads to more accurate results in comparing the conductivity of rods is the following. Let us assume that the two rods have the same section, and that a similar condition of surface is given to them, by covering them with some opaque varnish, or by polishing and electroplating with silver. The two ends of the rod are brought to constant but different temperatures, say by surrounding one end with boiling water, and the other with melting ice. To leave one end exposed to the

air and heat the other by a lamp which burns very regularly is an inferior method.

The middle part of the rod, at which the following determinations of temperature are made, is protected by screens from the radiation of the source of heat. The distribution of temperature after a time becomes constant. When this state has been arrived at the temperatures of three points of the rod equally distant from each other, I, II, III, are ascertained. The excess of temperature over that of the surrounding air may be called t_1 , t_2 , t_3 .

Let us call

$$\frac{t_1 + t_3}{t_2} = n$$

The same course of proceeding is now gone through with the other rod. The excess of temperature at the three points at the same distance from each other as before we call T_1 , T_2 , T_3 , and also—

$$\frac{T_1 + T_3}{T_2} = N$$

Then the two conductivities κ_1 and κ_2 are in the ratio :—

$$\frac{\kappa_2}{\kappa_1} = \frac{\log \left(\frac{n}{2} + \sqrt{\frac{n^2}{4} - 1} \right)}{\log \left(\frac{N}{2} + \sqrt{\frac{N^2}{4} - 1} \right)}$$

The temperatures may be determined by plunging small delicate thermometers into holes, as small as possible, bored in the rod, and filled with oil, mercury, or fusible metal. The equal distribution of heat through the rods must, however, be interfered with by the frequent interruption in the flux caused by the holes filled with a substance different from that of the bar. It is, therefore, better to use a thermo-element. Two wires of equal length made of two metals (bismuth-antimony; iron-german-silver; platinum-iron) are soldered together at one end, and at the other to copper wires. If the former soldering be placed at the point of which the temperature is to be measured, and the two junctions with the copper be kept at a known temperature (say by ice at 0°), an electromotive force results. This is measured by connecting the ends of the copper wires with a galvanometer and observing the deflection. For small differences of temperature (up to about 20°) the current strength may be taken as proportional to the difference of temperature. It is, therefore, only necessary to measure the current strength for a known difference *once*, in order to deduce the temperature from any

observation. For greater differences, or when the ordinary thermo-multiplier is used, in which the current strength cannot be calculated from the deflections, a table is constructed empirically by observing the deflections for certain known temperatures. From this a table for use is prepared by interpolation.

The experiments of MM. Wiedemann and Franz, the results of which have been given previously, were made by the method just described, using thermo-elements for the measurements of temperature.

256. **Absolute conductivity.**—In the preceding methods the bar is so long that the further end is not sensibly warmer than the surrounding air, and, moreover, the calculation of the results of the experiments rests upon several assumptions of which it has been ascertained by other investigations that they are not strictly true.

Thus it is assumed that Newton's law of cooling (which asserts that the quantity of heat lost or gained by a body in a second is proportional to the difference between its temperature and that of the surrounding medium) holds true for all parts of the surface. Now, Dulong and Petit, as will be shown afterwards, have proved that this law is not so general as Newton supposed. Further, it is assumed that all parts of a cross section of the bar have the same temperature, and also that the conductivity is independent of the temperature, which is not the case.

Professor J. D. Forbes, by a method which excluded some of these questionable assumptions, investigated the *absolute* conductivity of wrought iron, that is, the absolute quantity of heat which flows through a slice of given area and thickness of the substance in a definite time, if a constant difference of temperature be maintained at the opposite faces of the slice. The end of the bar was heated by a bath of melted lead kept at a uniform temperature, screens being interposed to protect the rest of the bar from the heat radiated by the bath. The temperatures at other points were observed by means of thermometers inserted in small holes drilled in the bar, and kept in metallic contact by fluid metal. In order to determine the loss of heat by radiation at different temperatures a precisely similar bar, with a thermometer inserted in it, was raised to about the temperature of the bath, and the times of cooling down through different ranges were noted. The conductivity of one of the two bars experimented on varied from $\cdot 01337$ at $0^{\circ}\text{C}.$, to $\cdot 00801$ at $275^{\circ}\text{C}.$, and the corresponding numbers for the other bar were $0\cdot 00992$ and $0\cdot 00724$, the units being the foot, the minute, the degree (of any scale), and the foot-degree of the same scale; that

is, the heat required to raise the temperature of one cubic foot of water one degree, from the zero-point (from 32° to 33° on Fahrenheit's scale). Professor Forbes and Sir W. Thomson made also absolute determinations of the conductivity of the soil or rock at three localities in or near Edinburgh. Expressed in the same units as are used above, they are—

Trap rock of Carlton Hill . . .	0'000268
Sand of Experimental garden . . .	0'000169
Sandstone of Craigleith Quarry . . .	0'000689

These determinations were derived from observations on the temperature of the soil, as indicated by thermometers having their bulbs buried at depths of from 3 to 24 feet. The annual range of temperature diminished rapidly as the depth increased ; and this diminution of range was accompanied by a retardation of the times of maximum and minimum.

257. **Conductivity of liquids.—Convection.**—Liquids are considered practically as almost absolute non-conductors, except mercury and melted metals. Let a tall narrow glass vessel, having a cake of ice at the bottom, be filled with strong alcohol at 0° . Let two thermometers be immersed in it, one near the surface, and the other at half the depth. If the alcohol be inflamed at the surface, the thermometer near the surface will rise, but that which is at the middle of the depth will be scarcely affected, and the ice at the bottom will not be dissolved.

Bodies in the gaseous state are probably still more imperfect conductors than liquids.

The equilibrium of temperature is, however, maintained in liquid and gaseous bodies by other means, which are more prompt in their action than the conductivity even of the solids which possess that quality in the highest degree. When strata of fluids, whether liquid or gaseous, are heated they become by expansion relatively lighter than those around them. If they have any strata above them, which generally happens, they rise by their buoyancy, and the superior strata descend. There are thus two systems of currents established, one ascending and the other descending, by which the heat imparted to the fluid is transfused through the mass, and the temperature is equalised.

To this means of equalising the temperature of, and diffusing heat through, liquids and gases the name of *convection* has been given. The action of convection will appear from *figs.* 95 and 96, while the almost entire absence of conductivity in a liquid may be proved by means of the simple apparatus shown in *fig.* 97.

In *fig.* 95 heat is applied to the lower part of a vessel

containing any liquid. An increase of temperature will soon be manifested throughout the liquid, which becomes heated by the transportation of its particles in quick succession. The particles nearest to the source of heat become heated first; they thereby become also specifically lighter than the particles which are above them and more removed from the source of heat; hence the colder particles descend while the hotter ascend, a succession of rapid changes which continues until the whole mass is raised to that constant temperature which has already been defined as its boiling point. These motions may be rendered visible by placing in the flask a few pieces of solid litmus or bran. The coloured liquid or bran will be seen to rise up the centre of the flask and descend down its sides. Fig. 96 represents a convection apparatus due to Faraday.

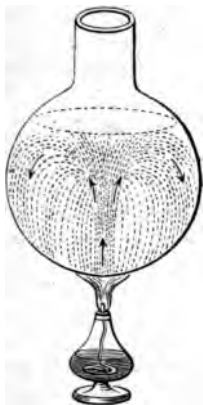


Fig. 95.

In both vessels water is placed mixed up with a little bran. In the upper vessel an upward current will be distinctly seen in tube *m*, and at *n* a downward current will be observed.

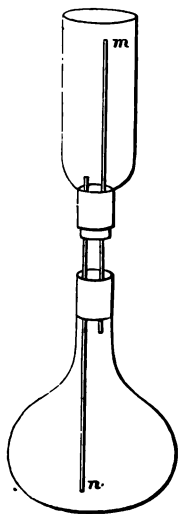


Fig. 96.

Fig. 97 represents a test-tube nearly filled with water, and some ice, weighted by a piece of wire wrapped round it, is placed in it. By inclining the tube, and heating the surface of the liquid by means of a spirit lamp the liquid at the top may be made to boil, while the ice at the bottom remains unmelted. On the other hand, if the ice is placed on the top of the liquid, and the test tube heated by applying the flame below the bottom of the tube, the ice will soon melt, because in this case the water heated at the bottom of the test tube rises upwards and parts with its heat to the ice.

258. Conducting power of water.—

The small conducting power of water can be inferred from the experiment represented in *fig. 97*. But it can also be very strikingly demonstrated by the apparatus shown in *fig. 98*. A vessel of tin has a lateral opening, closed by a cork through which a thermo-

meter passes. If cold water, w , is contained in the vessel, the thermometer will indicate its temperature. If now a layer of hot oil, l , be poured upon the water, or even alcohol is burnt on the surface, the thermometer, although only about one-tenth of an inch below the hot liquid, will require a considerable lapse of time before it rises 1° .

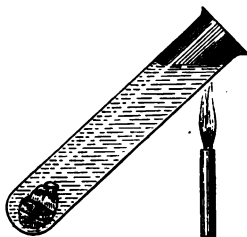


Fig. 97.

Despretz made some investigations on the conducting power of water, and found its conductivity very small, yet capable of measurement. He used a cylinder of wood, 1 metre high and about 0.3 metre in diameter, which was filled with water. In the side of this cylinder twelve thermometers were arranged one above another, their bulbs being all in the same vertical line through the middle of the liquid column. On the top of the liquid rested a metal box, which was filled with water at 100° , frequently renewed during the course of the experiment. In this manner Despretz observed that

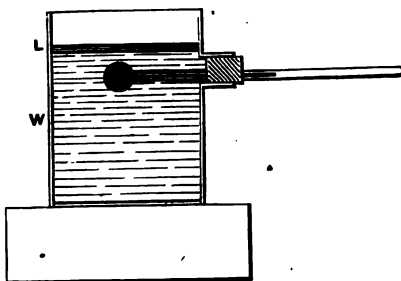


Fig. 98.

the temperature of the thermometers rose gradually, and that a long time—about 30 hours—was required before the temperature at all points of the column of water became stationary. Their permanent differences formed a geometric series; both were very small and very inappreciable after the sixth thermometer. His experiments gave the conductivity of water as being $\frac{1}{95}$ th that of copper. In the above table (Art. 248) water should therefore be marked 0.9, and would still be much behind the last in the list. It might be expected that heat was conducted to the liquid from the solid wood which formed the sides of the cylinder, but the temperature was higher in the axis of the cylinder than near the sides, which proves that no conduction from the sides of the cylinder took place, but that the elevation of temperature was really due to the passage of heat downwards through the liquid.

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Professor *Guthrie* has been led to conclude from recent experiments that the conducting power of water is higher than that of any other liquid except mercury. With this conclusion agree some experiments made by Despretz on the conduction of heat in stratified liquids. A wooden cylindrical vessel 72 centimetres high and 40 centimetres in diameter was half-filled with nitrobenzene of specific gravity 1·20, and water was poured on the top. Ten horizontal thermometers served for the observation of the stationary temperatures, whilst a constant source of heat acted on the surface of the water. In experiment 1 the bulbs of the thermometers were placed in the axis of the cylinder; in experiment 2 they reached only to the middle of its semi-diameter. The following table gives the distances of the thermometers from the surface of separation of the two liquids, and the excesses of the observed temperatures above the temperature of the surrounding atmosphere:—

Thermometers		Experiment No. 1		Experiment No. 2	
		Millimetres	°	Millimetres	°
Water	A	133·7	41·26	137·44	41·15
	B	101·8	31·17	110·34	32·01
	C	69·1	23·62	80·25	24·76
	D	41·5	18·66	49·25	19·16
	E	17·5	15·68	15·90	14·83
Nitrobenzene	F	17·5	11·83	15·90	10·68
	G	46·6	7·09	41·90	6·84
	H	75·7	4·48	69·80	4·36
	I	106·2	2·56	101·40	2·42
	K	138·6	1·50	133·00	1·11

On graphically representing these results it is found that the excesses of temperature are nearly in geometrical proportion. The mean ratio of the geometrical series, taking the difference of distances as 17·5, is:—

	Exper. 1.	Exper. 2.
In water . . .	0·861	0·863
In nitrobenzene . . .	0·739	0·703

At the boundary of the two liquids Despretz had unfortunately not placed any thermometers. Here the curves representing the results separate; from the water to the nitrobenzene, which conducts on the average 3·7 times less easily, the calculated temperature rises about 2° or 3°.

259. **Conductivity of gases.**—Air and all other gases without exception are bad conductors, and a flow of heat can only take place through them easily by an actual movement of their molecules, which must be produced by heating that portion of a gas which is lower than the remainder; the heated molecules thus become less dense and rise, while the heavier portion gradually descends and becomes heated in turn. A space filled with air cannot be heated from above, for the heated molecules in the upper portion of the mass remain where they are, while those below them remain at rest and become heated only very slowly. When the motion of gaseous molecules is restrained they do not convey much heat, even if they are heated from the side or from below. The free motion of the air in a given space may be prevented by dividing the whole space, by numerous partitions, into smaller spaces. A free current is no longer possible under these circumstances, and such a space could no longer be effectually heated even by convection. It is this circumstance, already referred to in the case of asbestos, which increases considerably the resistance to thermal conduction of such substances as fur, feathers, ashes, fabrics, straw, etc. The air remains stationary between their particles, and offers thus an obstacle to the propagation of heat by preventing a free circulation of heated molecules.

Experiments on the conductivity of gases are rendered difficult on account of the effects of convection and radiation, and the subject is still a matter of controversy as far as regards the *relative* conductivity of gases. Dulong and Petit observed that a hot body cools more rapidly in hydrogen than in air. Hence they concluded that hydrogen is a better conductor than air. The cooling action of air may be rendered manifest by sending a voltaic current through a coil of platinum wire. It glows bright red, but on stretching out the coil so as to form a straight wire the glow instantly sinks, so as hardly to be seen. This effect is due to the freer access of the cold air to the stretched wire. Again, if a stretched platinum wire is fixed between two metallic rods which pass through the sides of a vessel capable of being connected with an air-pump, the wire may be heated by a weak voltaic current but barely luminous enough to be seen while the vessel is full of air. The surrounding air carries off a portion of the heat of the wire; when the air is exhausted the wire glows more brightly than before; when air is allowed to re-enter the wire for a time is quite quenched, in fact, rendered perfectly black, but its feeble glow is restored after the air has ceased to enter. The same effect in a greatly

increased degree is obtained if hydrogen is used instead of air, as *Grove* has observed. If the vessel with the wire in the preceding experiment be exhausted, and the wire is almost white-hot, the air which is allowed to enter cannot do more than reduce the whiteness to bright redness ; but if hydrogen enters instead of the air, the wire is totally quenched ; and even after the receiver has been filled with the gas and the inward current has ceased, the glow of the wire is not restored. If the intensity of the current be increased, the wire will become red-hot while surrounded by hydrogen, but would infallibly be fused were no hydrogen there. This can be easily proved by removing the hydrogen when the wire is fused. This extraordinary cooling power of hydrogen is by some physicists ascribed to the great mobility of its particles, which enables currents to establish themselves in this gas with greater facility than in any other—in other words, the effects described are referred to convection. Professor *Magnus*, however, ascribes the chilling of the wire to conduction. He places the platinum wire along the axis of a narrow glass tube filled with hydrogen, so as to impede the formation of currents. Although in this case the wire is surrounded by a mere film of the gas, and the presence of currents in the ordinary sense is scarcely to be assumed, the film shows itself just as competent to quench the incandescence as when the wire is caused to pass through a large vessel containing the gas. Professor *Magnus* also heated the closed top of a vessel, and found that the heat was conveyed more quickly from it to a thermometer, placed at some distance below the source of heat when the vessel was filled with hydrogen, than when it was filled with air. He found this to be the case even when the vessel was loosely filled with cotton wool or eider-down. These experiments on the greater conductivity of hydrogen as compared with air have, however, in the opinion of Professor *Tyndall*, not quite established the conclusions drawn from them by their originator, and the former physicist thinks the experimental question of gaseous conduction still an open one.

The following are some of the experiments made and the results obtained by Professor *Magnus*:—A glass tube, 10 centimetres long and 2 centimetres wide, had one end closed by fusion, and the other by an air-tight cork. Through the cork passed a thermometer and two narrow glass tubes, which could be closed by means of stopcocks. The small tube served for filling the larger tube with different gases ; while the thermometer, whose bulb was in the middle of the tube, indicated the temperature of the interior. The whole apparatus was placed in a glass flask,

in which water was kept boiling, so as to surround the apparatus during the experiment by an envelope of vapour of constant temperature. The time was now observed which elapsed while the thermometer rose from 20° to 80° , and from 20° to 90° , the interior of the tube being filled with a different gas in each series of experiments. Magnus found :—

Name of gas.	From 20° to 80° .	From 20° to 90° .
Atmospheric air .	3.5 minutes.	5.25 minutes.
Hydrogen . . .	1.0 „	1.4 „
Carbonic acid .	4.25 „	6.3 „
Ammonia . . .	3.5 „	5.5 „

Since the effect of currents is reduced to a minimum by this arrangement, and their action must on the whole be nearly the same for all gases, these experiments establish certainly a striking difference of behaviour between hydrogen and other gases.

In another series a cylindrical space was heated from above by boiling water contained in a vessel. The cylinder containing the gas had a lateral opening, closed by a cork, through which a thermometer passed in a horizontal position. The bulb of the thermometer was protected against radiation from the top by a little shield of cork, and the medium surrounding the gas was maintained at a constant temperature. At the pressures mentioned in the following table, the stationary excess of the internal over the external temperature (15° C.) was found for the various gases as follows :—

Name of gas	Pressure in millimetres	Excess of temperature	Pressure in millimetres	Excess of temperature	Pressure in millimetres	Excess of temperature
Atmospheric air .	759.4	9.6	356.0	10.0	11.6	11.7
Oxygen	771.2	9.6	—	—	11.0	11.6
Hydrogen	760.0	13.0	517.7	12.5	11.7	11.8
Carbonic acid . . .	750.4	8.2	309.1	9.3	16.4	11.3
Carbonic oxide . .	760.0	9.5	—	—	11.0	11.6
Nitrous oxide . . .	760.0	8.8	—	—	12.0	11.5
Marsh gas	771.3	9.4	306.8	7.3	12.0	11.6
Olefiant gas . . .	749.1	9.0	319.2	9.9	19.8	11.7
Ammonia	770.3	8.1	267.7	9.4	15.4	11.0
Cyanogen	760.0	8.8	—	—	14.0	11.4
Sulphurous acid .	757.3	7.8	301.1	9.1	11.4	11.0

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The last column, with a mean value of $11^{\circ}47$, represents the effect of nearly unimpeded radiation in a vacuum. Now, all gases, with the exception of hydrogen, show a smaller excess of the temperature in a denser medium than in a less dense, which proves that the effect of radiation is counteracted by an absorption which exceeds the conduction. But hydrogen exhibits the opposite behaviour; the transmitted heat in its denser state is greater, which indicates a conductive action similar to that of the metals.

260. **Causes which influence the conductivity.**—The conducting power of all bodies as previously mentioned, is diminished by pulverising them, or dividing them into fine filaments. Thus sawdust, when not too much compressed, is one of the most perfect nonconductors of heat. A casing of sawdust is found to be the most effectual method of preventing the escape of heat from the surface of steam-boilers and steam-pipes.

If, however, the sawdust be either much compressed on the one hand or too loosely applied on the other, it is not so perfect a nonconductor. In the one case, the particles, being brought into closer contact, transmit heat from one to another; and in the other case, the air circulating too freely among them, convection-currents are established by which the heat is transfused through the mass.

To produce, therefore, the most perfect nonconductor, the particles of the body must have naturally little conductivity, and they must be sufficiently compressed to prevent the circulation of currents of air among them, and not sufficiently compressed to give them a facility of transmitting heat from particle to particle by contact.

261. **Examples.**—The animal economy presents numerous and beautiful examples of the fulfilment of these conditions. It is generally necessary to the well-being of the animal to have a temperature higher than that of the medium which it inhabits. In the animal organisation there are processes carried on by which heat is generated. This heat has a tendency to escape, and to be dissipated at the surface of the body, and the rate at which it is dissipated depends on the difference between the temperature of the surface of the body and the temperature of the surrounding medium. If this difference were too great, the heat would be dissipated faster than it is generated, and a loss of heat would take place, which, being continued to a certain extreme, would destroy the animal.

Nature has provided an expedient to prevent this, which varies in its efficiency according to the circumstances of the climate and habits of the animal.

The plumage of birds is composed of materials which are bad conductors of heat, and are so disposed as to contain in their interstices a great quantity of air without leaving it space to circulate. For those species which inhabit the colder climates a still more effectual provision is made, for, under the ordinary plumage, which is adapted to resist the wind and rain, a still more fine and delicate down is found, which intercepts the heat which would otherwise escape through the coarser plumage. Perhaps one of the most perfect insulators of heat is swan's-down.

The wool and fur of animals are provisions obviously adapted to the same uses. They vary not only with the climate which the species inhabits, but in the same individual they change with the season. In warm climates the furs are in general coarse and sparse, while in cold countries they are fine, close, light, and of uniform texture, so as to be almost impermeable to heat.

The vegetable not less than the animal kingdom supplies striking illustrations of this provision. The bark, instead of being hard and compact, like the wood which it clothes, is porous, and in general formed of discontinuous laminæ and fibres, and, for the reasons already explained, is a bad conductor of heat, and thus prevents such a loss of heat from the surface of the wood under it as would be injurious to the tree.

A tree stripped of even a considerable portion only of its bark perishes, as an animal would if stripped of its fleece or a bird of its plumage.

Man is endowed with faculties which enable him to fabricate for himself covering similar to that which nature has provided for other animals ; and where his social condition is not sufficiently advanced for the accomplishment of this, his object is attained by the conquest of inferior animals, whose clothing he appropriates.

Clothes are generally composed of some light nonconducting substances which protect the body from the inclement heat or cold of the external air. In summer, clothing is intended to keep the body cool ; in winter, warm. Woollen substances are worse conductors of heat than cotton, cotton than silk, and silk than linen. A flannel shirt more effectually intercepts heat than a cotton, and a cotton than a linen one.

What the plumage does for the bird, wool for the animal, and clothing for the man, snow does in winter for the soil. The farmer and the gardener look with dismay at a hard and continued frost which is not preceded by a fall of snow. The snow is nearly a nonconductor, and, when sufficiently deep, may be considered as absolutely so. The surface may therefore fall to

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a temperature greatly below 0° , but the bottom in contact with the vegetation of the soil does not share in this fall of temperature, remaining at 0° , a temperature at that season not incompatible with the vegetable organisation. Thus the roots and young shoots are protected from a destructive cold.

The gardener who rears exotic vegetables and fruit trees protects them from the extreme cold of winter by coating them with straw, matting, moss, and other fibrous materials which are nonconductors.

If we would preserve ice from dissolving, the most effectual means would be to wrap it in blankets. Ice-houses may be advantageously surrounded with sawdust, which keep them cold by *excluding* the heat, by the same property in virtue of which it keeps steam-boilers warm by *including* the heat.

Air being a bad conductor of heat, ice-houses are sometimes constructed with double walls, having a space between them. This expedient is still more effectual, if the space be filled with loose sawdust.

Glass and porcelain are slow conductors of heat, which explains the fact that vessels of this material are so often broken by suddenly pouring hot water into them. If it be poured into a glass tumbler, the bottom, with which the water first comes in contact, expands: but the heat not passing freely to the upper part, this expansion is limited to the bottom, which is thus forced from the upper part, and a crack is produced.

When wine-coolers have a double casing, the external space is filled with a nonconductor.

When a solid body—a globe, for example—is heated at the surface, the heat passes gradually from the surface to the centre. The temperature of the superficial stratum is greater, and the temperature of the centre less than those of the intermediate parts, and the temperature of the successive strata is gradually less, proceeding from the surface to the centre.

But if the globe be previously heated, so as to have an uniform temperature from the centre to the surface, and be allowed to cool gradually, the superficial stratum will first fall some degrees below the stratum within it. This latter will fall below the next stratum proceeding inwards; and in the same way each successive stratum proceeding from the surface to the centre will attain a temperature a little lower than the stratum under it, the temperatures augmenting from the surface to the centre.

After an interval, of greater or less duration, according to the magnitude of the globe, the conductivity and specific heat

of the matter of which it is composed, the temperature to which it has been raised, the temperature of the surrounding medium, and other circumstances to be considered in the next chapter, it will be reduced to a uniform temperature, which will ultimately be that of the surrounding medium.

If a mass of fluid metal be cast in a spherical mould, the surface only will be solidified in the first instance. It will become a spherical shell, filled with liquid metal. As the cooling proceeds, the shell will thicken, and after an interval of time, the length of which will depend on the circumstances above mentioned, the ball will become solid to its very centre, the last portion solidified being that part of the metal which is at and immediately around the centre.

It is evident that the superficial stratum will first cease to be incandescent ; and in the same way each successive stratum proceeding from the surface to the centre will cease to be incandescent before the stratum within it.

If in the process of cooling, and after the globe ceases to be red hot, it were cut through the centre, it would be found that the central parts would be still incandescent ; and if its magnitude were sufficiently considerable, it would be found that even after the superficial stratum had been reduced to a moderate temperature, strata nearer the centre would be red hot, and the central part still fluid.

The interval which must elapse before the thermal equilibrium would be established might be hours, days, weeks, months, years, or even a long succession of ages, according to the magnitude and physical qualities of the material composing the globe.

The cylinder of the hydraulic press by which the tubes of the Britannia bridge were elevated was formed of a mass of fluid iron weighing 22 tons. This enormous casting, after being left in the mould for three days and nights, was still red hot at the surface. After standing to cool in the open air for ten days, it was still so hot that it could only be approached by men well inured to heat.

The torrents of liquid lava which flow from volcanoes become solid on their external surface only to a certain thickness. The lava in the interior of this shell still continues fluid. The stream of lava thus forms a vast tube, within which that portion of the lava still liquid flows for a long period of time. Months and even years sometimes elapse before the thermal equilibrium of these volcanic masses is established.

The globe of the earth itself presents a stupendous example

of the play of these principles. The vicissitudes of temperature incidental to the surface extend to an inconsiderable depth. At the depth of a hundred feet, in our climates, they are completely effaced. At this depth the thermometer no longer varies with the seasons. In the rigour of winter and the ardour of summer it stands at the same point. This stratum, the depth of which in any locality depends on various physical conditions is called the stratum of invariable temperature. It is found to be at Paris at the depth of 86 feet. The thermometer in the vaults under the Observatory at that depth has continued without variation at $11^{\circ} 82$ C. = $53^{\circ} 276$ Fahr. for more than fifty years. Near Edinburgh, Professor Forbes found that the variation of temperature did not penetrate to more than 40 feet.

At greater depths the temperature increases, but is always in the same locality invariable for the same depth. An increase of temperature takes place in descending, at the rate of one degree F. for every $54\frac{1}{2}$ feet of depth. Thus, the water which issues from the Artesian wells at Grenelle near Paris, and which rises from a depth of 1800 feet, has a constant temperature of $27^{\circ} 7$ C. = 82° Fahr.

It is apparent that the earth is a globe undergoing the gradual process of cooling, and that each stratum proceeding inwards towards the centre augments in temperature. It follows, therefore, that a part at least of the superficial heat of the earth proceeds from within. It is certain, nevertheless, by taking into account all the conditions of the question, that the cooling goes on so slowly as to have no sensible influence on the temperature at the surface, which is therefore governed by the solar heat, and the heat of the medium or space in which our globe, in common with the other planets, moves. It has been computed that the quantity of central heat which reaches the surface in a year would not suffice to dissolve a cake of ice a quarter of an inch thick.

The globe of the earth, therefore, manifesting the effects of a mass which, having been at some antecedent period at an elevated temperature, is undergoing the process of gradual cooling from the surface inwards, it is nearly certain that its central parts are still in a state of incandescence and fusion.

262. **Numerical expression for conductivity.**—A numerical expression for the measure of conductivity of substances is obtained in the following way. Let there be a plate of some substance, of indefinite surface, 1 foot thick, bounded by parallel planes, and let a constant difference of temperature be maintained between them of 1° C. Then a constant temperature will

be obtained along every plane parallel to the boundaries, but a different one along a line perpendicular to the boundaries. At some point in this line, m feet distant from the colder side, the temperature is m° higher than at the colder side, m being less than unity. Through 1 square foot of each plane parallel to the boundaries, and through the boundaries themselves flows the same quantity of heat; now, the quantity of heat which under these circumstances flows through different substances is a measure of conductivity of these substances. Thus for two kinds of iron per minute the quantity was found to be 0.01337, 0.00992 thermal units respectively. If this quantity for some other body is L , the thickness of the plate = d , and the constant temperature on both sides t_1, t_2 , then the heat passing in one minute through every plane parallel to the two planes, and having an area of s square feet, is

$$\frac{L s (t_1 - t_2)}{d} \text{ units per minute.}$$

In this equation L represents the coefficient of *internal* conductivity of the substance, heat being conducted in this case only through the molecules of the same substance. But two different substances in contact will also cause a flow of heat, as long as they are at unequal temperatures. Thus, let a plate having an area of one square metre, and being 1" thick, have a constant temperature difference of 1° between the two opposite faces by keeping one side at 0° and the other at 1° . Let the heat passed through in 1 second be L ; let a, b be any other temperatures maintained constantly at both opposite sides, then $\frac{L(a-b)}{d}$ = heat passing through the section. Now, if c is the temperature of the air on one side, c' that on the other side, we must have

$$\begin{aligned} \frac{L(a-b)}{d} &= h(c-a) \\ &= h'(b-c') \end{aligned}$$

because on the supposition of a constant temperature being maintained at both sides, the same quantity of heat must enter on one side which leaves the plate on the other side. In this equation h, h' are called coefficients of *external* conductivity.

263. More recent experiments on conductivity in gases.

—Dr. Narr has very recently made experiments on heat-conduction and the rate of cooling in hydrogen, nitrogen, air, and carbonic acid—from which the following conclusions are drawn.

1. The results arrived at by Dulong and Petit (see next chapter) do not express the true law of the variation of the

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rate of cooling of a heated body in a gas with the temperature, inasmuch as it gives only the cooling effect of the gas.

2. The cooling effects of different gases differ very considerably, and gases must be ranged, with respect to this effect, not according to their chemical but rather according to their physical character, since hydrogen and carbonic acid—two gases differing very widely in specific gravity and in capacity for heat—likewise exhibit the greatest difference of cooling power, whereas nitrogen and atmospheric air, which are characterised by almost identical physical constants, likewise exhibit almost equal rates of cooling.

3. Calculations made to trace the dependence of the observed temperatures on the times of cooling by means of the formula,

$$\log. \tau_0 - \log. \tau = a_1 x + a_2 x^2,$$

showed that in all cases the coefficient a_2 has a very small value, which, with exception of the data of observation relating to hydrogen, was negative. Hence it appears that, for most gases, the deviations from Newton's law of the proportionality of the rate of cooling of a body to the excess of its temperature above surrounding objects are inconsiderable, and that hydrogen exhibits a deviation in the contrary sense.

4. Calculations relating to cooling in a vacuum give also a very small value for the coefficient a_2 , so that the deviations of the rates of cooling calculated from the formula

$$v = m \tau$$

from the rates actually observed were but slightly greater than those relating to cooling in hydrogen. For these reasons Narr regards it as highly probable that Newton's law is the true expression for the cooling effect due to radiation alone.

Professor *Stefan* has also very recently further extended the experimental researches into the conductivity of gases. From experiments with double-walled thermometers of brass or copperplate, having the space between the metallic envelopes filled with the gas under examination, he concludes that the conducting power of air is nearly 20,000 times less than that of copper, and 3400 times less than that of iron. His experiments confirm the conclusions deduced from modern physical theories, that the conducting power of any particular gas is independent of its density; also the conclusion deduced by Professor Maxwell from the theoretical considerations, that the conducting power of hydrogen is seven times as great as that of air.

264. **Summary of the results of experiments.**—1. The mathematical theory of conduction is very complex, but it may be assumed that the heat conducted is approximately proportional to the temperature difference.

2. The temperatures along a bar decrease in a geometrical ratio, if the distances from the source of heat increase in an arithmetical series.

3. The conductivity is proportional to the square of the distances for which the differences in the temperature of the bar and that of the surrounding air are equal.

4. The mean values of the coefficients of conductivity may be derived approximately from the following numbers, given on page 332, as the results of the experiments by Franz and Wiedemann, viz. : silver = 1000; copper, 736; brass, 231; zinc, 190; tin, 145; iron, 119; lead, 85; platinum, 84; German silver, 63; bismuth, 18, by adding $\frac{1}{3}$ of the number to it, and dividing by 10. Thus, for copper :

$$\text{coeff. of conductivity} = 736 + \frac{736}{3} = 98.$$

5. In crystals of the regular system the conductivity is equal in all directions. In others only in the plane of the same axis.

In the regular system there is a *sphere* of isothermals; in those of the second and third system it is an *ellipsoid* of rotation, in the three last a triaxial ellipsoid. Wood in the direction of its fibres is a better conductor than across their direction.

CHAPTER XIII.

RADIATION.

265. Nature of radiation. Difference between radiation and conduction.—Heat, like light, is propagated through space by radiation in straight lines, and its rays, like those of light, are subject to transmission, reflection, and absorption by such bodies as they encounter in various degrees.

All that is established in optics respecting the reflection of light from unpolished, perfectly and imperfectly polished surfaces, its refraction by transparent media, its interference, inflexion, and polarisation, may, with little modification, be applied to the rays of heat submitted to similar conditions.

In *radiation* the motion of the molecules is supposed to be communicated to another body by means of the motion of the intermediate ether which fills universal space and the interstices between the molecules of matter. The number of vibrations per second of the ether necessary for heat begins with 60 billions and

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extends to about 800 billions. From 400 to 600 billions light is also produced. Near 800 billions the heat effect becomes very small. Heat and light radiation are otherwise identical. A body is only heated by heat rays if the vibrations of its ether are transferred to its molecules, that is, if it absorbs heat rays. If this is not the case, the ether-vibrations are simply transmitted, and the body does not change its own temperature. The progressive motion of heat rays has the same velocity as that of light-radiation. Through empty space, through air and other bodies, radiation of heat proceeds in all cases with the velocity of light.

That the intervening medium remains itself unheated by the traversing heat rays may be inferred from a variety of observations and experiments. In turning round, the face is no longer heated by a fire at a distance, hence the air itself is not heated through by the fire ; similarly a thermometer falls, if a screen is placed between it and the fire ; the upper layers of the air and universal space are cold, while the earth is warmed by the sun. Prévost made the following experiment : a flame was placed on one side of the jet of a fountain, a sensitive thermometer on the other ; the thermometer rose, although the water remained at the same temperature between the source of heat and the thermometer, because it was constantly renewed. Another experiment may easily be made thus : water is allowed to pass through a hollow convex lens, which acts as a burning-glass ; the water maintains its temperature while an easily inflammable body may be ignited in the focus of the converging heat rays. The spectrum of the sun and other bodies shows the identity of light and heat rays, but also that there exist dark and luminous heat rays. Dark rays are less refrangible, and make therefore a less number of vibrations per second. Finally, solar light and heat appear always together, hence their velocity is the same.

In *conduction* the molecular motion passes from one part of a body to another, from one body to another, from molecule to molecule. Hence it is supposed that in conduction heat passes from one molecule to the other through the envelopes of ether which may be assumed to form a kind of shell round each molecule. Conduction is therefore radiation at very small distances, and heat thus passing from molecule to molecule must clearly take longer time for its propagation, and without exception all intermediate particles must be heated. This slow propagation involves loss by radiation and conduction to neighbouring bodies, hence the temperature must gradually diminish the

farther the heat is conducted. Besides, molecules of different bodies are in the most varying positions toward one another, hence a different velocity of molecular motion. Hence *good* and *bad conductors*. Metals are the best conductors, gases the worst, for the great distances between the molecules make radiation more prominent, as in empty space, without the intermediate heating of the molecules.

Metal and wooden bars placed in a source of heat show the difference between good and bad conductors. Silver and iron show differences among good conductors. Decrease of temperature with distance from source of heat shows itself in all these cases plainly. This difference of conducting power is readily shown by the thermopile. Small cylinders of silver, copper, iron, bismuth, stone, wood, are placed upon the pile. After the cylinder has the same temperature as the pile there is no deflection of the galvanometer. Then the same small iron disc, taken from boiling water, is placed upon the cylinders successively: different times are required for each metal for the same deflection.

Convection takes place, when liquid or gaseous bodies have at a lower level a higher temperature than at an upper. In consequence of expansion the lower layers become lighter, rise by their buoyancy, and convey thus to the upper layers a higher temperature.

In this manner water is heated by a flame applied below or at the sides. Warming by gas rests on convection. Winds are produced by currents due to convection. It will be seen, from this brief outline of facts, that radiation differs essentially from the modes of heat-propagation hitherto considered.

266. **Instruments for the study of radiant heat.**—Common thermometers take too long a time for showing the temperature required to be shown; hence small differences of temperature when instantaneously occurring cannot be shown by them. In Leslie's differential thermometer, air, which expands considerably, is used to show quickly a sensible expansion, and hence difference of temperatures.

Leslie's differential thermometer, described in Art. 41, page 32, has two bulbs, filled with air; one is covered with lamp-black, and both are connected by a tube. A thread of coloured sulphuric acid indicates the changes of temperature.

In Melloni's (Nobili's) thermopile antimony and bismuth couples are used, and the first antimony and last bismuth bar connected with the galvanometer. By means of this instrument temperature differences of $\frac{1}{5000}$ th of a degree on the centigrade scale can be accurately determined.

267. **Thermal analysis of solar light.**—It is demonstrated in the treatise on OPTICS, in this series, art. 178, page 123, that solar light is a compound consisting of rays differing from one another, not only in their luminous qualities of colour and brightness, but also in their thermal and chemical properties.

Let *s s'*, fig. 99, represent a pencil of solar light transmitted through a prism *A B C*, so as to be resolved into a divergent fan of rays, and to form a spectrum, as described in OPTICS, art. 179, page 125. Let *L* and *L'* be the limits of the luminous spectrum. If the bulb of a thermometer be placed at *L*, it will not indicate any elevation of temperature; and if it be gradually moved downwards along the spectrum, it will not begin to be sensibly affected until it arrives at the boundary of the violet and blue spaces, where it will show an increased temperature. As it is moved downwards from this point, the temperature will continue to increase until it is brought to the lower extremity *L'* of the luminous spectrum. If it be then removed below this point, instead of falling to the temperature of the medium around the spectrum, as might be expected, and as would in fact happen if no rays of heat transmitted through

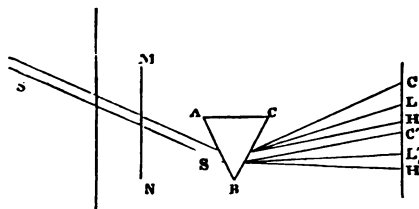


Fig. 99.

the prism passed below *L'*, it will descend slowly and gradually and will in some cases even show an increased temperature to a certain small distance below *L'*. In fine, it will be found that the thermometer will not fall to the temperature of the surrounding medium until it arrives at a certain distance *H'* below *L'*, the extremity of the luminous spectrum.

From this and other similar experiments, it is inferred that thermal rays which are not luminous, or at least not sensibly so, enter into the composition of solar light, and that these rays are differently refrangible, their mean refrangibility being less than the mean refrangibility of the luminous rays.

It is also demonstrated in OPTICS (article 205, page 150) that the chemical rays which enter into the composition of solar light are also differently refrangible, and have a mean refrangibility greater than that of the luminous rays.

According to this view of the constitution of solar light, the prism $A B C$ must be regarded as producing three spectra, a chemical spectrum $c c'$, a luminous spectrum $L L'$, and a thermal spectrum $H H'$, the relative position of which will more strikingly appear from *fig. 133*, page 147, in the treatise on OPTICS, in this series. The luminous or chromatic spectrum, the only one visible, lies between, and is partly overlapped by, the other two, the chemical spectrum extending a little above, and the thermal a little below it. If we imagine a screen $M N$ placed before the prism, composed of a material pervious to the luminous, but impervious to the chemical and thermal rays, then the luminous spectrum $L L'$ alone will remain, and neither a thermometer, nor chloride of silver or any other chemical substance will be appreciably affected when exposed in it. If the screen $M N$ be pervious only to the thermal rays, then the luminous and chemical rays will be intercepted, and the thermal spectrum $H H'$ alone will be manifested. The thermometer exposed in it will indicate the variations of calorific influence already explained, showing the greatest thermal intensity at and a little beyond that point at which the red extremity of the luminous spectrum would have been found, had the luminous rays not been intercepted.

268. Refrangibility dependent on the nature of medium.

If prisms composed of different materials be used, it will be found that the mean refrangibility of the thermal rays will vary according to the material of the prism, and will also depend on the nature of the heat; consequently, the position of the point of greatest thermal intensity will be subject to a like variation.

If a hollow prism be filled with water or alcohol, the point of greatest thermal intensity will be about the middle of the yellow space of the luminous spectrum. If a prism of sulphuric acid, or a solution of corrosive sublimate, be used, it will be in the orange space. With a crown glass prism it will be in the red space; and with one of flint glass, a little beyond that space; that is, in our figure, below it.

269. Invisible rays.—In the preceding explanation, the solar light is regarded as consisting of three distinct species of rays, the chemical, the luminous, and the thermal. It is not necessary, however, for the explanation of these phenomena, to adopt this hypothesis. The light may be considered as consisting of rays which, differing in refrangibility, possess the other physical qualities also in different degrees. So far as the sensibility of thermometers enables us to detect the thermal property, it ceases to exist at a certain point, near the boundary of the blue and violet spaces; but the diminution of thermal

intensity, in approaching this point, as indicated by the thermometer, is very gradual ; and it cannot be denied, that a thermal influence may exist above that point, which is, nevertheless, too feeble to affect the thermoscopic tests which are used. In the same manner it may be maintained that a chemical influence may exist below the point c' , but too feeble to affect any of the tests which have been applied to it.

But it may be asked, if all the component rays possess all the properties in different degrees, how happens it that the chemical rays above L , and the thermal rays below L' , are not visible ? To this it may be answered that the presence of the luminous quality is determined by its effect on the eye ; and the discovery of its presence must therefore depend on the sensibility of that organ. To pronounce that there are no luminous rays beyond the limits of the chromatic spectrum, would be equivalent to declaring the sensibility of the eye to be unlimited. Now, it is notorious that the sensibility of sight, in different persons, is different ; and, even in the same individual, varies at different times. Circumstances render it highly probable that many inferior animals have a sensation of light, and a perception of visible objects, where the human eye has none ; and it is therefore consistent with analogy to admit the possibility, if not the probability, that the invisible thermal rays below L' , and the invisible chemical rays above L , may be of the same nature as the other rays of the spectrum, all enjoying the luminous, thermal, and chemical properties in common ; the apparent absence of these properties in the extreme rays being ascribable solely to the want of sufficient sensibility in the only tests of their presence which we possess.

Fortunately, however, the experimental results of physical science, though deductions from them may be facilitated by these and other hypotheses, are not dependent on them, but on observed facts and phenomena, and cannot, consequently, be modified by theories.

270. Radiation of invisible rays.—If a hole be made in the screen upon which the prismatic spectrum is thrown, in the space $L' H'$ below the red extremity of the spectrum upon which the invisible thermal rays fall, these rays will pass through it, and may be submitted to all the experiments on reflection, refraction, inflexion or diffraction, interference, and polarisation. This has been done, and they have been found to manifest effects similar to those exhibited by luminous rays.

It is shown in optics that when a body is either luminous, like the sun, or illuminated, like the moon, each point upon its

surface is an independent centre of radiation or *focus* from which rays of light diverge or radiate in all directions. It is the same with regard to heat. All bodies, whatever be their state or condition, contain more or less of this physical agency; and rays of heat accordingly issue from every point of their surface, as from a focus, and diverge or radiate in all directions through the surrounding space.

This being the case, it would follow that by such continual and unlimited radiation, bodies would gradually lose their heat, and indefinitely fall in temperature. It must be considered, however, that such radiation, being universal, each body, while it thus radiates heat, receives upon its surface the rays of heat which proceed from other bodies around it. So many of these rays as it absorbs tend to increase its temperature, and to replace the heat dispersed by its own radiation. There is thus between body and body a continual interchange of heat by radiation; and according as this interchange is equal or unequal, the temperature of the radiating body will rise or fall. If it radiate more than it absorbs, it will fall; if less, it will rise. If it absorb as much exactly as it radiates, its temperature will be maintained stationary.

Radiation takes place altogether from points either on the surface or at a very small depth below it. The circumstances which affect it have been first submitted to accurate study by a beautiful series of experiments made by the late Sir John Leslie. The principles on which his mode of experimenting was founded are easily explained.

271. **Reflection of heat.**—Let a cubical canister of tin (*fig. 100*) be placed in the axis of a parabolic metallic reflector *M*, in the focus *f* of which is placed the bulb of a sensitive differential thermometer. If the canister be placed with one of its sides at right angles to the axis of the reflector, and be filled with boiling water, the thermometer will instantly show an increase of temperature caused by the heat radiated from the surface of the canister, and collected into a focus upon the ball by the reflector. A perspective view of the apparatus is given in *fig. 101*.

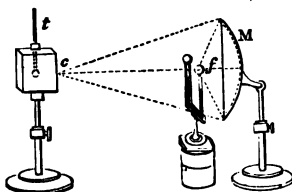


Fig. 101.

The experiment may be varied by filling the canister with liquids at all temperatures, with snow, and with freezing mixtures producing artificially very low temperatures. The surface of

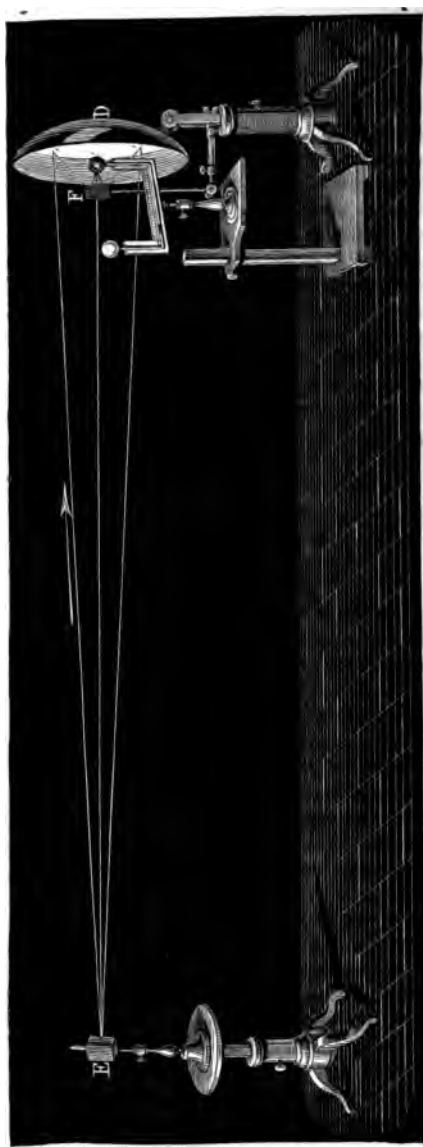


Fig. 101.

the canister may be varied in material by attaching to it different substances, such as paper, metallic foil, glass, porcelain, &c. It may be varied in texture by rendering it rough or smooth, and in colour by any colouring matter. In this way the influence of all these physical conditions upon the radiation from the surface may be, and has been, ascertained.

The results of these experimental researches have been briefly as follows :—

I. The rate at which the radiating body loses or gains temperature, other things being the same, is proportional to the difference between its own temperature and that of the surrounding medium, where this difference is not of very extreme amount.

II. The intensity of the heat radiated is, like that of light, other things being the same, inversely as the square of the distance from the centre of radiation.

III. The radiating power varies with the nature of the surface, and its degree of polish or roughness. In general, the more polished a surface is, the less will be its radiation. Whatever tarnishes or roughens the surface of metal, increases its radiation. Metallic are in general less powerful radiators than non-metallic surfaces.

When the rays of heat encounter any surface, they are more or less reflected from it. Surfaces, therefore, in relation to heat, are perfect or imperfect, good or bad reflectors.

In the experiments above described, the reflecting powers of different surfaces were ascertained by constructing the concave reflector *M* of different materials, or by coating its surface variously, or, in fine, by submitting its surface to any desired physical conditions. Thus, when a reflector of glass is substituted for one of metal, the radiating surface of the canister remaining the same, it is found that the effect on the thermometer is diminished. Glass is, therefore, a less perfect reflector than metal. If the surface of the reflector be coated with lamp-black, no effect whatever is produced on the thermometer. Such a surface does not, therefore, reflect the thermal rays.

272. **Absorption.**—To determine the physical conditions which affect the absorbing power of a surface for heat, it is only necessary, in the experiment above described, to vary the surface of the bulb *f* of the differential thermometer, which is placed in the focus of the reflector, for, as the heat is radiated by *c* and reflected by *M*, it is absorbed by *f*. By coating the bulb of the thermometer, therefore, with metallic foil, paper, lampblack, and other substances, and by rendering it in various degrees rough and smooth, the effects of these modifications on the

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thermometer are rendered manifest, and the comparative absorbing powers are ascertained.

- In this way it has been ascertained that the same physical conditions which increase the radiation and diminish the reflection, increase the absorption. The best radiators are the most powerful absorbers and the most imperfect reflectors.

In the following table, the numbers in the first column express the radiating and absorbing powers of various substances, that of a surface covered with the smoke of a lamp (lampblack) being expressed by 100. The absorbing power of this surface is complete. The reflecting power is here given, as will be observed, as the complement of the absorbing power.

Names	Radiating and absorbing Powers	Reflecting Power
Smoke-blackened surface	100	0
Carbonate of lead	100	0
Writing paper	98	2
Glass	90	10
China ink	85	15
Gumlac	72	28
Silver foil on glass	27	73
Cast iron polished	25	75
Mercury (nearly)	23	77
Wrought iron polished	23	77
Zinc, polished	19	81
Steel	17	83
Platinum, thick coat, imperfectly polished	24	76
„ plate on copper	17	83
„ leaves	17	83
Tin	14	86
Metallic mirrors a little tarnished	17	83
„ nearly polished	14	86
Brass, cast, imperfectly polished	11	89
„ hammered	9	91
„ „ highly polished	7	93
„ cast, „	7	93
Copper coated on iron	7	93
„ varnished	14	86
„ hammered or cast	7	93
Gold plating	5	95
Gold deposited on polished steel	3	97
Silver, hammered and well polished	3	97
Silver, cast, and well polished	3	97

The numbers given in this table, which differ considerably from those originally determined by Leslie and others, have been obtained by the more recent elaborate experimental researches of MM. De la Provostaye and Desains. In these experiments an anomalous circumstance was observed on varying the angle of incidence of the thermal rays. It was found that, in the case of glass, the proportion of rays reflected increased with the angle of incidence, as happens with luminous rays, but that with polished metallic surfaces, the same proportion was reflected at all incidences up to 70° , and beyond this limit the proportion reflected, instead of increasing, as would have been expected, was greatly diminished.

273. **Thermal equilibrium.**—From all that has been so far explained it will be apparent that the state of thermal equilibrium is maintained among any system of bodies by a continual interchange of heat by radiation and absorption. The heat which each body receives from others in its presence, it partly absorbs and partly reflects. Those rays which it absorbs tend to raise its temperature ; and this temperature would soon rise above that which the thermal equilibrium requires, but that the body radiates heat from all points of its surface ; and the total quantity thus radiated is equal to the total quantity absorbed. If either of these quantities were permanently greater or less than the other, the temperature of the body would either indefinitely rise, or indefinitely fall, according as the heat absorbed or radiated might be in excess.

If a body, at any given temperature, be placed among other bodies, it will immediately affect them *thermally*, just as a candle brought into a room illuminates all bodies in its presence, with this difference, however, that if the candle be extinguished, no more light is diffused by it ; but no body can be *thermally extinguished*. All bodies, however low be their temperature, contain heat, and therefore radiate it.

If a ball of ice be brought into the presence of a thermometer, the thermometer will fall ; and hence it was erroneously inferred that the ice emitted *rays of cold*. The effect, however, is a simple consequence of the principle just explained. The ice and the ball of the thermometer both radiate heat, and each absorbs more or less of what the other radiates towards it. But the ice, being at a lower temperature than the thermometer, radiates less than the thermometer, and therefore the thermometer absorbs less than the ice, and consequently falls.

If the thermometer placed in presence of the ice had been at a lower temperature than the ice, it would, for like reasons, have,

risen. *The ice in that case would have warmed the thermometer.*

274. **Transmission of heat.**—When the rays of heat are incident on the surface of certain media, they penetrate them in greater or less quantity, according to the nature and properties of the medium, just as rays of light pass through bodies which are more or less transparent or diaphanous.

Media which are pervious to heat are said to be *diathermanous*, and those which are impervious are called *athermanous*.

Bodies are diathermanous in different degrees, or altogether athermanous, according to their various physical characters, their thickness, the state of their surface, the nature of the heat which is incident upon them, and other conditions.

275. **Melloni's thermoscopic apparatus.**—Nearly all the knowledge we possess in this branch of the physics of heat is the result of the recent researches of M. Melloni. The thermoscopic apparatus contrived and applied with singular felicity and success by him, consisted of a thermo-galvanic pile acting upon a highly sensitive galvanometer. It will be explained hereafter that if the thermal equilibrium be disturbed in certain metallic

combinations, an electric current will be produced, the intensity of which will be proportional to the difference of temperature, and that the force of such a current can be measured by the deviation it produces of a magnetic needle, round which it is conducted spirally along a coil of metallic wire coated with a nonconducting substance.

The general form and arrangement of this apparatus, and the manner of applying it to thermal researches, are represented in *figs. 102, 103, 104, and 105.*

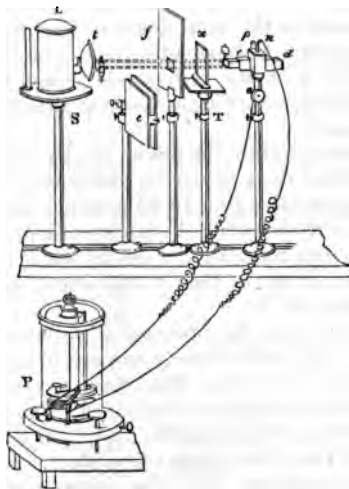


Fig. 102.

Upon the stand *s* is placed the source of heat which is submitted to experiment. Those which M. Melloni selected were a lamp *L*, with a concave reflector *t*; a spiral wire of platinum *H* (*fig. 103*) rendered incandescent by the flame of a spirit-lamp; a plate of

copper 1 (*fig. 104*), blackened with smoke, and raised to the temperature of nearly 400° by a spirit-lamp; and, in fine, a cubical canister κ (*fig. 105*), similar to those used by Leslie.

On the stand τ was placed the body x , through which the rays of heat were to be transmitted, and which was formed into a thin plate. An athermanous screen f was interposed, having in it an aperture to limit the pencil of rays transmitted to x . Another athermanous screen was placed at c , movable upon a joint by which the pencil proceeding from the lamp could be intercepted or transmitted at pleasure.

The thermo-voltaic pile was placed at p , having one end presented to the thermal pencil, and movable in a case fitting it, in which it was capable of sliding. Its poles p and n were connected by conducting wires with the galvanometer ρ , the needle

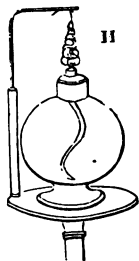


Fig. 103.

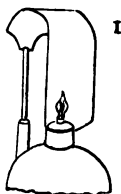


Fig. 104.

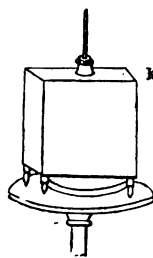


Fig. 105.

of which indicated by its deflection the varying intensity of the heat by which the pile was affected.

276. **Results of Melloni's experiments.**—The series of experiments made with this apparatus gave the remarkable, and in many respects unexpected, results which we shall now briefly state.

The only substance found to be nearly perfectly diathermanous was rocksalt. Plates of this substance transmit nearly all the heat which enters them, no matter from what source. Of the incident rays 7·7 per cent. are reflected from both surfaces of the plate, and the whole of the remaining 92·3 per cent. are transmitted. There is no sensible absorption.

Bodies in general are less athermanous the higher the temperature of the radiator.

Media are not diathermanous in proportion as they are transparent. On the contrary, certain media which are nearly opaque are highly diathermanous, while others which are highly transparent are nearly athermanous. Thus, black glass and

plates of smoked quartz, so opaque that the disc of the sun in the meridian is barely visible through them, are much more diathermanous than plates of albin, which are very transparent; and plates of quartz smoked to opacity are more diathermanous than when clean and transparent. In like manner, black glass is more diathermanous than colourless glass.

The thermal pencil is composed of rays, some of which are absorbed, and others transmitted by certain media. This effect is altogether analogous to that which is produced by coloured media on light. If a pencil of solar light be incident upon red glass, the red rays alone will be transmitted, those of the other colours being absorbed; but if the red light transmitted through such a plate be received upon a second red plate, there will be no further absorption; at least, so far as depends on the colour of the light. In like manner, when a thermal pencil enters certain diathermanous media, a part of its rays is intercepted, another being transmitted. If these latter rays be received upon another plate of the same diathermanous substance, they will pass freely through it without further absorption.

It is therefore inferred that such a medium decomposes by absorption the thermal pencil, in the same manner as a coloured transparent medium decomposes by absorption a pencil of white light. This inference is confirmed by the fact that different partially diathermanous media absorb different constituents of the thermal pencil. Thus we may cause its entire absorption by causing it successively to pass through two media, each of which absorbs the rays transmissible by the other.

This is also analogous to the effects of coloured transparent media upon luminous pencils. If a pencil of solar light be successively incident upon two plates, one of red and the other of the complementary tint of bluish-green, it will be wholly absorbed, the second plate absorbing all the rays transmitted by the first.

The partial absorption produced by such imperfectly diathermanous media is not effected at the surface. The rays are absorbed gradually as they pass through the medium. This, however, is not continual. All absorption ceases after they have passed through a certain thickness, and the rays transmitted by a plate of that thickness would, in passing through a second plate of the same substance, undergo no further absorption.

Glass and rock crystal are each partially diathermanous, the thermal rays transmitted and absorbed, however, being different. If a thermal pencil pass through a plate of glass of a certain

thickness, a part of the rays composing it will be absorbed. If the rays transmitted be received on another similar plate of glass, they will be all, or nearly all, transmitted, no further absorption taking place. But if these rays thus transmitted by the glass be received upon a plate of rock crystal of sufficient thickness, a portion of them will be absorbed. Now if the glass and the rock crystal had each the power of absorbing the rays transmitted by the other, their combination would be absolutely athermanous, just as two plates of coloured glass would be opaque, if each transmitted only the colours complementary to those transmitted by the other.

277. Diathermancy.—It appears from the researches of Melloni that the physical conditions which render bodies more or less diathermanous have no connection with those which affect their transparency. Water is one of the least diathermanous substances, although its transparency is so nearly perfect. If, therefore, it be desired to transmit light without heat, or with greatly diminished heat, it is only necessary to let the rays pass through water, by which they will be strained of a great part of their heat.

If the quantity of radiant heat transmitted through air be expressed by 100, the following numbers will express the quantity transmitted through an equal thickness of the substances named below .—

Air	100	Rape oil	30
Rock salt (transparent). . .	92	Tourmaline (green) . . .	27
Flint glass	67	Sulphuric ether	21
Bisulphide of carbon . . .	63	Gypsum	20
Calcareous spar (transparent)	62	Sulphuric acid	17
Rock crystal	62	Nitric acid	15
Topaz, brown	57	Alcohol	15
Crown glass	49	Alum, crystals	12
Oil of turpentine	31	Water	11

It appears, therefore, that of all solid bodies rocksalt is the most diathermanous, and alum the least so. Of all liquids, bisulphide of carbon is the most, and water the least, diathermanous.

It is evident from this table, that bodies are not diathermanous and transparent in the same degree. Rocksalt is less transparent but more diathermanous than glass.

It has been found that the power of thermal rays to penetrate an imperfectly diathermanous body is augmented by raising the temperature of the radiator. This is rendered very apparent in the case of glass, which is much more diathermanous to heat



Fig. 107.

If two concave parabolic reflectors, shown in *fig. 106*, are so placed that their axes shall be in the same direction, their concavities being presented one to the other, any radiator of heat placed in the focus of either will produce a corresponding effect upon a thermometer placed in the focus of the other, the rays of heat issuing from the radiating body being twice reflected and collected in the focus of the second reflector.

Let R and R' , *fig. 106*, be two such reflectors. If red-hot charcoal be placed in the focus F of one, it will ignite amadou or any other easily inflammable substance in the other, even though the distance between the reflectors be twenty or thirty feet.

If a sensitive thermometer, such as the differential thermometer be placed at R' , it will show an increase or diminution of temperature, according as a hot or cold body is placed at F . If a small globe filled with hot water be placed there, an increase of temperature will be indicated; and if the globe be filled with snow or with a freezing mixture, a decrease will be manifested. A perspective view of the apparatus is given in *fig. 107*, where D and E are the reflectors, C the source of heat placed in the focus of D , and F the object affected by the reflected rays in the focus of E .

Vessels intended to hold liquids and maintain them at a higher temperature than that of the surrounding medium, should be constructed of materials which are bad radiators. Thus tea-urns, tea-pots, &c., are best adapted for their purpose when made of polished metal, and worst when of black porcelain. A tea-kettle keeps water hot more effectually if clean and polished, than if covered with the black of soot and smoke. Polished fire-irons remain longer before a hot fire without being heated than rough unpolished ones.

A polished stove is a bad radiator; one with a rough and blackened surface a good radiator. The latter is therefore better adapted for warming an apartment than the former.

The helmet and cuirass worn by cavalry is a cooler dress than might be imagined, the polished metal being a good reflector of heat, and throwing off the solar rays.

When the external air, as generally happens, is at a lower temperature than the air included in the room, it will frequently be observed that a deposition of moisture will take place upon the inner surface of the panes of glass in the windows. This is produced by the vapour suspended in the atmosphere of the room being condensed by the cold surface of the glass. If the external air in this case be at a temperature below 0° , the deposition on the inner surface of the glass will be congealed, and a rough coating of ice will be exhibited upon it.

Let two small pieces of tinfoil be fixed, one upon a part of the external surface of one of the panes, and the other upon the internal surface of another pane, in the evening ; it will be found in the morning that that part of the internal surface of the pane upon which the foil is placed externally will be nearly free from ice, while the surface of the internal foil will be more thickly covered with ice than the parts of the inner surface of the glass which are not covered with foil. These effects are easily explained by radiation. When the tinfoil is placed on the external surface, it reflects the heat which strikes on that surface and protects that part of the surface which is covered from its action. The heat radiated from the objects in the room striking on the inner surface of the glass penetrates it, and encountering the foil attached to the exterior surface, is reflected by it back again through the glass, and its transmission into the external atmosphere is intercepted ; the portion of glass, therefore, opposite to the tinfoil, is subject to the action of the heat radiated from the chamber, but protected from the action of the external heat. The temperature of that part of the glass is therefore less depressed by the external atmosphere than the temperature of those parts which are not covered by tinfoil. Now, glass being a bad conductor of heat, the temperature of that part opposite to the external foil does not immediately affect the remainder of the pane, and consequently we find that, while the remainder of the interior surface of the pane is thickly covered with ice, the portion opposite the tinfoil is comparatively free from it. On the contrary, when the tinfoil is applied on the internal surface, it reflects perfectly the heat radiated from the objects in the room, while it admits through the dimensions of the glass the heat proceeding from the external atmosphere. The portion of the glass, therefore, covered by the tinfoil, becomes colder than any other part of the pane, and the tinfoil itself partakes of this temperature, which is not raised by the effect of the radiation from objects in the room, because the tinfoil itself is a good reflector and a bad absorber. Hence the tinfoil presents a colder surface to the atmosphere in the room than any other part of the surface of the pane, and consequently receives a more abundant deposition of ice.

280. Formation of Dew.—A clear unclouded sky in the absence of the sun radiates but little heat towards the earth ; consequently, if good radiators be exposed to such an aspect, they must suffer a fall of temperature, since they lose more by radiation than they receive.

Let a glass cup, for example, be placed in a silver basin, and

exposed during a cold night to a clear sky, it will be found in the morning that a copious deposition of moisture will have been made on the glass, from which the silver vessel is perfectly free. Reversing the experiment, let a silver cup be placed in a glass basin, and similar results will ensue, the basin being perfectly covered with moisture, from which the silver cup is free. This is easily explained: the metal, being a bad radiator of heat, preserves its temperature: the glass, being a good radiator of heat, loses by radiation much more than it receives, and consequently its temperature falls, and it condenses the vapour in the air around it.

The results of experiments of this kind suggested to Dr. Wells his celebrated theory, by which he explained the formation and accompanying phenomena of dew.

According to what has been explained, it appears that those objects which are good radiators, will when exposed to a clear sky at night, become colder than the surrounding atmosphere, and will consequently condense the vapour suspended in the air around them; while objects which are bad radiators will not do this. Grass, foliage, and other products of vegetation are in general good radiators. The vegetation, therefore, which covers the surface of the ground in an open country on a clear night will receive a deposition of moisture from the atmosphere, while the objects which are less perfect radiators, such as earth, stones, &c., do not in general receive such depositions. In the close and sheltered streets of cities the deposition of dew is rarely observed, because there the objects are exposed to diffused and reciprocal radiation, and an interchange of heat takes place which maintains their temperature.

The effect of the radiation of foliage is strikingly manifested by the following experiment:—Of two thermometers, if one be laid among leaves and grass, and the other suspended at some height above them, the latter will be observed to fall at night many degrees below the former.

In a cloudy night dew is not deposited, because in this case, although vegetation radiates as perfectly as before, the clouds also radiate, since their temperature is far higher than that of the planetary spaces, and hence an interchange of heat takes place between them and the surface of the earth, by which the fall of temperature producing dew is prevented.

281. **Artificial ice.**—Artificial ice is sometimes produced in hot climates by the following process:—A position is selected, not exposed to the radiation of surrounding objects, and a quantity of dry straw is spread on the ground, on which pans of

porous earthenware are disposed in which the water to be cooled is placed. The water radiates heat into space, and receives no heat in return. The straw upon which the vessels are placed being a bad conductor, intercepts the heat, which would otherwise be imparted to the water in the vessels from the earth. The porous nature of the pans allowing a portion of the water to penetrate them, produces a rapid evaporation, by which a considerable quantity of the heat of the water is carried off in a latent state by the vapour. Heat is thus lost both by evaporation and radiation, and the temperature of the water in the pans is diminished until it attains the freezing point. In the morning the water is found frozen, and is collected and placed in cellars surrounded with straw or other bad conductors, which prevent its liquefaction.

282. **Recent experiments and theories.**—It has already been indicated in several preceding articles that heat is now supposed to be a kind of motion—a motion of the molecules of a body, not a motion of translation in the ordinary sense. Suppose that a red-hot copper ball is suspended in the air; we see it glow, the glow sinks, the ball becomes obscure; in popular language the ball cools. Bearing in mind the modern conception of the nature of heat, we must regard this cooling as a loss of molecular motion. But motion cannot be lost, it must be transmitted to something. Hence the question must naturally arise, to what the molecular motion is transferred in this case? Partly the motion is undoubtedly transmitted to the air, which surrounds the ball, rises in a heated column, and passes in an ascending stream over it. But it may easily be shown that not the whole, not even the chief part, of the molecular motion of the ball is dissipated in this way. If the ball were placed in a vacuum it would still cool. Rumford suspended a small thermometer by a single fibre of silk in the middle of a glass globe which had been exhausted by mercury and represented the perfect vacuum of a barometer; he found that the calorific rays passed to and fro across the vacuum, thus proving the transmission of heat to be independent of air. Davy showed that the heat rays from the electric light pass freely through an air-pump vacuum. If the motion of the molecules is not entirely nor in greater part communicated to the air, it must be communicated to something else. Now, according to the theory now universally received, heat as well as light consists of a vibratory motion of the molecules of the hot body. Further, a close examination of the phenomena connected with light and heat has led to the conclusion that all space is occupied by a substance almost in-

finitely elastic, through which the pulses of light and heat, originated by the molecular vibrations of a luminous or hot body, make their way. The vibrations of the molecules are thus communicated to the ether in which the molecules swing, and are propagated in waves.

Hence it follows that when a red-hot ball, as in the supposition stated previously, gradually cools, the molecules of the ball oscillate in a resisting medium on which their motion is expended, and which transmits it on all sides with inconceivable velocity. The oscillations competent to produce light are soon exhausted; the ball becomes dark, still its molecules continue to oscillate, and the oscillations continue to be taken up by the ether and to be transmitted on all sides. The ball cools as it thus loses its molecular motion, but no cooling to which it can be practically subjected can entirely deprive it of its motion. In other words, all bodies, whatever may be their temperature, are radiating heat. From every body that exists in the medium surrounding the cooling ball waves are speeding forth, some of which strike upon the ball and restore again a portion of its lost motion. But the motion thus received by the ball is far less than that which it communicates, and the difference between them expresses the loss of heat. As long as this state continues the ball will continue to show a falling temperature; its temperature will sink until the quantity of heat it emits is equal to the quantity which it receives, and at this point its temperature becomes constant. Thus, every superficial atom of each mass is sending forth its waves, which cross those that move in the opposite direction, every wave asserting its own individuality. When the sum of motion received is greater than that given out, warming is the consequence; when the sum of motion given out is greater than that received, chilling takes place. This view of the occurrences that take place when bodies cool or warm by radiation is due to *Prevost*, and has been called the *theory of exchanges*.

283. **Analogies between light and radiant heat. Reflection.**—The thermo-electric pile used in researches on radiation of heat is always provided with a cone which is silvered inside, and is intended to augment the action of feeble radiations; by converging them upon the face of the thermo-electric pile, which it does by reflection. In articles 271 and 279 some experiments were already described which showed that heat is capable of being reflected like light from suitable surfaces. That heat obeys the same laws in reflection which regulate the reflection of light may be shown by the thermo-pile and by a variety of experimental arrangements. Thus, let it be sup-

posed that a mirror carries perpendicular to its own plane a straight bar, and that the light of an electric lamp is projected in a compact beam upon the mirror, so that the angle which it makes with the bar, the angle of incidence, may be measured by a suitable arrangement. It will be found that the reflected beam takes such a direction that the angle which it makes with the bar, the angle of reflection, is exactly equal to the angle of incidence. This is precisely the law as given in the treatise on OPTICS (pages 23 and 24, arts. 41 and 42), with a description of some similar experiments for its demonstration. Now, in order to prove that radiant heat obeys precisely the same laws in reflection as light, it is necessary to interpose a plate of black glass, so black that no light whatever can pass through it, in the path of the beam of light emitted by the lamp. The plate, though opaque for the rays of light, is to some extent transparent for the obscure heat rays which are given out by the incandescent carbon points of the electric lamp together with the luminous rays. Hence, although all light is extinguished by the plate, if now the axis of the thermo-pile be placed in the same line of direction in which previously the reflected beam of light was sent forth by the mirror, the needle of a galvanometer, which was before at 0° , will swing immediately round to 90° ; when the pile is moved to the right or left of the direction of the reflected beam of calorific rays, the deflection immediately decreases. Thus the calorific rays have pursued the precise track of the luminous rays, and for them also the angle of reflection is equal to the angle of incidence.

In this experiment the heat is associated with light; but the law can be shown to hold good for rays emanating from a truly obscure body. If a warm copper ball be substituted for the electric lamp, the reflected beam of heat rays will still strike the thermo-pile only in a definite direction, which will be in accordance with the law of reflection.

Calorific rays, like luminous rays, proceed in straight lines through space. Thus, let the hot copper ball which when close to the pile causes the needle of the galvanometer to swing from 0° to 90° be removed to a distance from it of several feet, where it shows scarcely a sensible action. Its rays are transmitted into the space all round, and comparatively few of them reach the pile. But if now a tube of tin be placed between pile and ball, polished within, and therefore capable of reflecting, the ball being near one open end of the tube and the pile near the opposite end, then a number of calorific rays will strike the interior surface of the tube obliquely, will be reflected from side

to side of the tube, and thus be enabled to reach the pile. The consequence is that the needle which a moment ago showed no sensible action will swing round immediately.

From curved surfaces heat is similarly reflected, in accordance with the same laws which determine the direction of luminous rays reflected by curved surfaces. Thus, let a hot copper ball be placed at some distance from the pile, from which the conical reflector has been removed, so that the ball produces no action on the needle. If now a concave mirror, formed of copper coated with silver, be placed behind the ball in a definite position, the mirror will collect and reflect the calorific rays emitted by the ball towards the face of the pile, and a deflection of the needle will take place. On replacing the ball by a luminous object—for example, a lighted candle—and the pile by a screen, it will be found that the definite relative position of ball, mirror, and pile must be exactly the same to produce a calorific effect, as the relative position of candle, mirror, and screen, to produce upon the latter a luminous effect.

284. **Law of diminution with the distance.**—It has been stated in the treatise on OPTICS (art. 18, page 11), that the intensity of light which issues from a luminous point diminishes in the same proportion as the square of the distance from the point increases, and that this is a common property of all radiation. Hence we may conclude that the intensity of radiant heat diminishes with the distance in the same manner as that of light. For heat rays the law may be proved by the following experiment:—A narrow tin vessel has a side, coated with lamp-black, of a square yard in area. The vessel is filled with hot water, which converts the large surface into a source of radiant heat. A thermo-pile, with its face towards the radiating surface, and its conical reflector bearing inside a lining of black paper, so as to shut off all oblique radiation, is now placed at a certain distance from the hot vessel. The needle of the galvanometer will move, and will point steadily to some division on the scale as long as the temperature of the radiating surface remains sensibly constant. If now the pile be gradually withdrawn from the surface, it might be expected that the intensity of the heat will diminish and that the deflection of the galvanometer will diminish also in a corresponding degree. But when the pile is at double the distance the needle does not move, at treble the distance it is still stationary, and we may successively increase the distance four times, five times, and so on, without producing any effect on the needle. There is to all appearance no diminution at all of the intensity with the increase of distance. From

this experiment, however, although at first sight it might appear in contradiction with the law of propagation of heat above enunciated, Melloni derived an experimental proof of it. The reasoning from the experiment is as follows :—Let us imagine the hollow cone in front of the pile prolonged ; it would cut the radiating surface in a circle, and this circle is the only portion of that surface whose rays can reach the pile. All the other rays are cut off by the non-reflecting lining of the cone. When the pile is moved to double the distance the section of the cone prolonged encloses a circle exactly four times the area of the former one ; at treble the distance the radiating surface is augmented nine times, and so on. Now, the constancy of the deflection proves that the augmentation of the surface must be exactly neutralised by the diminution of the intensity. But the radiating surface augments as the square of the distance, hence the intensity of the heat must diminish as the square of the distance ; and thus the experiment, which might at first sight appear fatal to the law, demonstrates it in the most simple and conclusive manner.

285. **Differences in emissive power.**—It may be inferred from the previously explained conceptions as to the nature of that mode of propagation of heat which is called radiation, that the disturbance produced in the ether must depend upon the character of the oscillating molecule. One kind of molecule may be more unwieldy than another, and a single molecule could not be expected to produce so great a disturbance as a group of molecules oscillating in combination. Thus, when different bodies are heated we may expect that their molecules will not all create the same amount of disturbance in the ether. Some will communicate a greater amount of motion than others ; in other words, some will emit heat more copiously than others, for emission, or radiation, of heat, as now conceived, is nothing else but communication of motion from the particles of a heated body to the ether in which these particles are immersed and through which the motion is propagated. This is the modern explanation of the results on the different emissive powers of substances, already experimented on by Leslie, afterwards by Melloni, and stated in the preceding articles. Let a Leslie's cube (see Art. 271, *fig.* 100), made of pewter, have one side coated with a layer of gold, another with a layer of silver, another with a layer of copper, and the fourth coated with a varnish of isinglass. If the cube be filled with hot water, and, keeping it at a constant distance from the thermo-electric pile, its four faces are allowed to radiate in succession against the

pile, then the following effects will be seen : the gold produces scarcely any deflection ; the hot silver is equally ineffective ; the same is the case with copper ; but when the varnished surface is turned towards the pile, so much heat flows upon it that the needle swings suddenly to its stops. Only one inference can be drawn under these circumstances : through some physical cause or other the molecules of the varnish, when agitated by heat, communicate more motion to the ether than do the atoms of the metals. In other words, the varnish possesses a greater emissive power, or is a better radiator, than the metals. Similar results are obtained when hot water of the same temperature is poured into two vessels, one of silver, the other of earthenware, or one of pewter, the other of glass. The radiation from the earthenware and the glass is most copious, while that from the metal vessels is insignificant. Everyone can satisfy himself of these differences in emissive power by a very simple experiment. A small tin pan is blackened on one side by means of a turpentine or paraffine flame ; some water is then made to boil in it and the vessel removed from the flame. If now the back of each hand be held about one centimetre from the sides of the pan, one hand opposite to the blackened side, and the other to the bright side, the hand opposite to the blackened side will feel the heat much more than the other hand : the blackened surface radiates much more heat than the bright surface.

Let now one side of the cube be coated with whiting, another with carmine, a third with lampblack, and the cube, being filled with hot water, be first turned with the black side to the thermopile ; a considerable deflection of the needle will take place. If now the white side be presented to the pile, the needle remains stationary, proving that radiation from the white side is just as copious as from the black. When the red surface is turned towards the pile still no change takes place in the position of the needle, but if the uncoated side is placed opposite to the face of the pile, being at the same distance as the other faces were before, the needle instantly falls, proving that the metallic surface has an inferior radiating power. If three sides of the cube be coated respectively with black, white, and red velvet, and one face be left naked, it will be found that the velvet surfaces radiate alike, while the naked surface radiates less than any of them. Hence radiation from our clothes must be independent of colour.

It may, of course, be inferred that a vessel which presents outwards a surface of high emissive power will cool more rapidly than another with a surface of less emissive power, both starting at the same temperature.

286. **Relation between radiation and absorption.**—Between the power of a body to communicate motion to the ether, or to radiate, and its power to receive motion from the ether, or to absorb, there exists complete reciprocity. Suppose two sheets of tin, one coated with whiting, the other left uncoated, to be placed parallel to each other at a distance of about two feet asunder. To the edge of each sheet is soldered a screw, and into each screw the end of a copper wire is fastened, which thus stretches from sheet to sheet. At the back of each sheet is soldered one end of a little bar of bismuth, to the other end of which a wire is fastened. The two free ends of the two wires lead to the galvanometer, thus completing an unbroken circuit, in which the galvanometer is included. When the warm finger is placed on one of the bars—then from the principles of thermoelectricity (ELECTRICITY, chap. xii., page 231)—we know that an electric current is immediately developed, which passes from the bismuth to the tin, thence through the wire connecting the two sheets, thence round the galvanometer and back to the point from which it started. The needle of the galvanometer will move through a large arc in a definite direction; if the warm finger be then placed upon the bismuth at the back of the other plate, a large deflection in the opposite direction will be observed. When the finger is withdrawn the junction cools, and the needle moves to 0° . Let now exactly midway between the two sheets of tin a heated copper ball be placed. The ball will then radiate heat upon two surfaces equally, one of them a naked metallic one, the other coated with whiting. If both surfaces absorbed heat equally—that is, if both surfaces were equally ready to accept the motion of the ethereal waves—the bismuth junctions at the back would be equally warmed, and the electrical effect produced by warming one would be precisely neutralised, the other being warmed also and with equal intensity. But if one surface be a more powerful absorber than the other, a deflection of the galvanometer needle will be the consequence, and the direction of the deflection would tell us which is the better heat absorber; in this particular case it will be found that the coated face is the more powerful absorber. If in the same way lampblack and varnish be compared with tin, the two former will be found by far the best absorbers.

The reciprocity between radiation and absorption has been illustrated by Professor *Balfour Stewart* by means of experiments of great elegance and instructiveness. It is known from Melloni's researches on diathermancy that rocksalt is a bad absorber of thermal rays, while glass and alum possess high

absorptive powers, the glass, however, in a considerably less degree than the alum. Hence we should expect that the emissive power of these substances will be in the same order of position as absorbers. Experiment bears out this conclusion. In a copper vessel water is kept in a state of gentle ebullition. On the flat copper lid of the vessel are laid plates of glass and of rocksalt, until they assume the temperature of the lid. When the plate of heated rocksalt is fixed upon a stand in front of the thermo-electric pile, the deflection produced is so small as to be scarcely sensible: rocksalt, a bad absorber, is also a bad radiator of thermal rays. Let now a plate of heated glass take the place of the rocksalt: the needle of the galvanometer moves through a large arc, indicating that glass, a much better absorber, is also a better radiator. Finally, let a plate of alum be substituted for the glass. Alum cannot be heated to the same temperature as the glass or rock-salt in these experiments, because it melts at a lower temperature. Still, though the alum is thus less warm than the glass used, the emissive power of this highly absorptive substance is so great even at the lower temperature that the needle is deflected more energetically than in the case of the glass.

287. **Selective absorption.**—Bodies which are transparent to light are such because the luminous waves of the ether which excite light can pass through them without transferring their motion to the atoms. In coloured bodies certain waves are absorbed, while those which give the body its colour are transmitted without absorption. Through a piece of blue glass, or through a solution of sulphate of copper, the blue waves pass unimpeded, while the red waves are absorbed. Red glass, on the contrary, owes its colour to the fact that its substance can be traversed freely by the longer waves of red, while the shorter waves of blue are absorbed. It follows that since the blue liquid cuts off the rays transmitted by the red, and the red cuts off those transmitted by the blue, by combining both and placing them in the path of the beam, perfect opacity will be produced. A solution of permanganate of potash allows the red and blue rays to pass, but destroys the yellow. Thus, as regards light, bodies exercise an *elective* power, singling out certain waves for extinction and permitting others to pass; or, in accordance with present conceptions, transparency to waves of one length does not imply transparency to waves of another length. From this we might reasonably conclude that transparency to light does not necessarily imply transparency to radiant heat. This conclusion is fully borne out by experiment. In Arts. 276 and 277 results have

already been given which have been derived by experiment, and which prove that bodies like water and alcohol, which are transparent to luminous waves, are almost opaque to calorific rays. Bisulphide of carbon is transparent to light and heat. Among solid bodies, rock-salt and glass, both transparent for light, differ considerably in their transparency for heat, the rocksalt being highly diathermanous, while glass is practically rather opaque to heat rays. The following table gives a more complete statement of Melloni's results on the diathermancy of bodies than that given in Art. 277. The substances used were all reduced to a thickness of one-tenth of an inch (2·6 milimetres):—

Name of Substance	Transmission (percentage of total radiation)			
	From Locatelli's Lamp	From Incandescent Platinum	From Copper at 100°.	From Copper at 400°.
Rock salt . . .	92·3	92·3	92·3	92·3
Sicilian sulphur . .	74	77	60	54·0
Fluor spar . . .	72	69	42	33
Beryl . . .	54	23	13	0
Iceland spar . . .	39	28	6	0
Glass . . .	39	27	6	0
Rock crystal (clear) .	38	28	6	3
Smoky quartz . . .	37	28	6	3
Chromate of potash .	34	28	15	0
White topaz . . .	33	24	4	0
Carbonate of lead . .	32	23	4	0
Sulphate of baryta . .	24	18	3	0
Felspar . . .	23	19	6	0
Amethyst (violet) . .	21	9	2	0
Artificial amber . . .	21	5	0	0
Borate of soda . . .	18	12	8	0
Tourmaline (deep green) . . .	18	16	3	0
Common gum . . .	18	3	0	0
Selenite . . .	14	5	0	0
Citric acid . . .	11	2	0	0
Tartrate of potash . .	11	3	0	0
Natural amber . . .	11	5	0	0
Alum . . .	9	2	0	0
Sugar candy . . .	8	1	0	0
Ice . . .	6	0·5	0	0

This table does not only show that bodies differ in their transmissive power for heat, but also that, with the exception of rocksalt, the diathermancy of the bodies mentioned varies with the source of heat, in other words, with the quality of heat. Thus glass permits 39 per cent. of the rays of Locatelli's lamp to pass, and 24 per cent. of the rays from incandescent platinum, but transmits only 6 per cent. of the rays from a source of 400° , and is absolutely opaque to all rays emitted from a source of 100° C. For the explanation of these facts it must be considered that luminous rays are also calorific, but that the former—that is, the luminous thermal rays—have a shorter wave-length than the latter, the obscure thermal rays; and further that rays of different wave-lengths are also differently absorbed by bodies.

Clear ice, so highly transparent to light, transmits only 6 per cent. of the rays of the lamp, only 0.5 per cent. of the rays from incandescent platinum, and cuts off all rays from the two other sources. This indicates the fact, that by far the greater portion of the rays from Locatelli's lamp are obscure. Since luminous rays pass through a slice of ice like that used in these experiments without sensible absorption, and 94 per cent. of the rays from this source are absorbed by ice, this proportion must consist of obscure rays, for all obscure rays are totally absorbed by ice. Clear and smoky quartz are striking instances of differences between the transmissive power of substances for luminous and thermal rays. One kind is pellucid, the other dark brown; they differ strongly in the transmission of luminous rays, but, as seen from the table, their degree of diathermancy, although different for every source, is almost the same for each quality of heat.

Rocksalt was considered at first to be perfectly diathermanous, the 7.7 per cent. not transmitted being reflected by the two surfaces of the plate used. MM. de la Provostaye and Desains have, however, proved by accurate experiments that this substance is in reality not equally diathermanous for heat of different kinds, but that its diathermancy varies in some degree when the source of heat varies. Professor Balfour Stewart found that rocksalt is athermanous for rays issuing from a heated piece of the same substance, a discovery of the highest importance, as will be seen further on.

288. **Diathermancy of liquids.**—Melloni has also investigated the calorific transmission of the liquids which are enumerated in the following table. The source of heat was an argand lamp, furnished with a glass chimney, and the liquids were enclosed in a cell with glass sides, the thickness of the liquid layer being 9.21 millimetres, or 0.36 of an inch. The same

differences amongst liquids appear to exist, as regards their diathermancy, as is observed amongst solids, and water shows itself nearly as opaque in the liquid state as in the solid, as ice.

Name of Liquid	Transmission (percentage of total radiation)
Bisulphide of carbon	63
Bisulphide of sulphur	63
Protochloride of phosphorus	62
Essence of turpentine	31
Olive-oil	30
Naphtha	28
Essence of lavender	26
Sulphuric ether	21
Sulphuric acid	17
Hydrate of ammonia	15
Nitric acid	15
Absolute alcohol	15
Hydrate of potash	13
Acetic acid	12
Pyroligneous acid	12
Concentrated solution of sugar	12
Solution of rocksalt	12
White of egg	11
Distilled water	11

289. **Influence of thickness.**—When distilled water is contained in a drinking-glass it has no colour, but a sufficiently thick layer of water exhibits a decided colour. To exhibit the colour a tube, fifteen feet long, is placed in a horizontal position, its ends being stopped by pieces of plate-glass. At one end of the tube may be placed a strong light, like that of the electric lamp, sending a cylinder of light through the tube. The tube is half-filled with water, the upper surface of which divides the tube into two equal parts; thus half the beam is sent through air and half through water, and with a lens a magnified image of the adjacent end of the tube is thrown upon a screen. The image consists of two semicircles, one of which is formed by the light which has passed through the water, the other by the light which has passed through the air. Placed thus side by side we can compare them, and we shall find that the air semicircle is a pure white, the water semicircle is a bright and delicate blue-green. Thus, by augmenting the thickness through which the light has to pass, we deepen the colour.

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It appears from this that absorption takes place *within* the absorbing body; it is not an effect of surface merely—a certain thickness is requisite to effect the absorption.

That the same principle holds good for radiant heat has also been shown by Melloni. He used in his experiments with solid bodies plates of a thickness of 2·6 millimetres, as already stated. When the plates were made thinner a greater quantity of heat was transmitted, and we may render a highly absorptive substance as diathermanous as rocksalt by making the plate sufficiently thin. The following table gives results on the influence of thickness obtained by using a plate of glass :—

Thickness of plates	Transmission (percentage of total radiation)			
	From Locatelli's Lamp	From Incandescent Platinum	From Copper at 400° C.	From Copper at 100° C.
Millimetres				
2·6	39	24	6	0
0·4	54	37	12	1
0·07	77	57	34	12

These results show that there is a considerable increase in the percentage of transmitted rays if the plates are taken as thin as 0·07 millimetres, and that such plates will transmit 12 per cent. of the rays from a source for which they are totally opaque, if even only as thin as a little more than half a millimetre. With selenite the following results on the influence of thickness were obtained :—

Thickness of plates	Transmission (percentage of total radiation)			
	From Locatelli's Lamp	From Incandescent Platinum	From Copper at 400° C.	From Copper at 100° C.
Millimetres				
2·6	14	5	0	0
0·4	38	18	7	0
0·01	64	51	32	21

These experiments add evidence for the fact that absorption of heat takes place within the body, and is not a surface action.

290. **Quality of heat.**—The solar spectrum is, as has been stated already, luminous in the centre, calorific at the red end, and chemical at the opposite end. Most other sources of heat are similarly a heterogeneous assemblage of rays, and in general when such mixed rays enter a diathermic substance some are intercepted, others permitted to pass. If now a collection of calorific rays, which have already passed through a diathermanous plate, is permitted to fall upon a second plate of the same material, the second plate must be more diathermanous to the transmitted rays of the first than the first plate was to the original collection of rays. The first plate, if sufficiently thick, has already extinguished, in great part, the rays which the substance is capable of absorbing, and the residual rays pass therefore freely through a second plate of the same substance. The first plate has in this case actually *sifted* the original beam, and hence the sifted beam possesses as regards the second plate a much higher penetrative power. The heat after being transmitted by the first plate differs from the heat before transmission and consequent sifting, and this difference is termed a difference of *quality of heat*. From the beam as a whole certain components have been withdrawn, and hence the proportion of the incident heat upon the second plate to that transmitted is different to the proportion of the incident and transmitted heat taken with reference to the first plate. Thus, if in the path of the beam from a lamp plates of rocksalt, alum, bichromate of potash, and selenite be successively placed, each plate 2·6 millimetres in thickness, let the heat emergent from these respective plates fall upon a second series of the same thickness; out of every hundred units of this heat the following proportions are transmitted:—

Rock salt	.	.	.	.	.	.	92·3
Alum	.	.	.	.	.	.	90
Chromate of potash	.	.	.	.	.	.	71
Selenite	.	.	.	.	.	.	91

We thus see considerable differences, if these results are compared with Melloni's table of diathermancy. Chromate of potash transmits 34 per cent. of the original beam from a Locatelli's lamp, and 71 of the sifted; selenite transmits only 14 per cent. of the original beam, but of the beam which has been sifted by itself it transmits as much as 91 per cent. It is similar with alum. But in rocksalt the transmissions are the same, an obvious consequence of the thermal transparency of

the substance for rays of all those qualities which have been employed in these experiments.

A very striking experiment to illustrate the effect of sifting is due to Professor Tyndall. A differential thermometer, with clean glass bulbs, so sensitive that the slightest touch of the hand causes a depression of the thermometric column, is so placed that by means of a lens the powerful beam of an electric lamp may be brought to convergence upon one of the bulbs, which is exactly in the focus of the lens. The air in the bulb is thus traversed by a beam of intense power, and we should expect an immediate depression of the thermometric column in consequence of the expansion of air by heat. Nothing, however, happens—not the slightest depression is discernible. The reason is that the beam before it reaches the bulb is already sifted by the glass lens used to concentrate it, and having passed through air before it reaches the bulb, nothing is left in it which can be sensibly absorbed by the air within the bulb. Hence the hot beam passes through both air and glass without warming either. But if the bulb is now covered with lampblack heat is absorbed, the air expands, and the thermometric column is rapidly depressed.

291. **Absorption by gaseous matter.**—Professor Tyndall has in recent years much enriched physical science by most elaborate and long-continued researches on the behaviour of gases and vapours with reference to heat rays, researches which have led to results of the highest importance, of which only an outline can be given here.

In gaseous bodies the intermolecular spaces are so greatly augmented, and the molecules are so free from mutual interaction and consequent entanglement, that we should be justified in concluding that gases and vapours furnish a perfectly open door for the passage of the calorific waves. This has until quite recently been the universal belief; and as experiments on atmospheric air led to the conclusion that there was no evidence of absorption, the opinion appeared to be verified by experiment.

Professor Tyndall's apparatus consisted essentially of a hollow cylinder, about four feet in length and two and a half inches in diameter, placed in a horizontal position, and capable of being exhausted of, or filled with, various gases and vapours by tubes in the side of the cylinder. The two ends could be closed by rocksalt plates. The source of heat could be placed opposite to one end, while opposite to the other the thermopile and galvanometer were erected. Behind the thermopile a second

source of heat was placed, which acted as compensator, and enabled the experimenter to use a powerful flow of heat and at the same time to discover small variations in the quantity of heat that fell upon the pile.

Dry air was found to be incompetent to stop a single calorific wave; it is practically a vacuum as regards rays of heat. Oxygen, hydrogen, and nitrogen, when carefully purified, exhibit the action of atmospheric air, and this is precisely what was supposed to be the deportment of all gaseous matter before Professor Tyndall's researches. But it was soon found that olefiant gas, for which common coal-gas might also be substituted, intercepts heat like an opaque body. Various other gases were found to show no different behaviour, but to absorb large quantities of calorific rays, as shown in the following table, in which the absorption is referred to air as unity:—

Name of Gas.	Absorption at 30 inches pressure
Air	1
Oxygen	1
Nitrogen	1
Hydrogen	1
Chlorine	39
Hydrochloric acid gas	62
Carbonic oxide	90
Carbonic anhydride	90
Nitrous oxide	355
Sulphide of hydrogen	390
Marsh gas	403
Sulphurous anhydride	710
Olefiant gas	970
Ammonia	1195

The most powerful tests applied did not disclose a difference between oxygen, hydrogen, nitrogen, and air. The more perfectly these gases are purified the more closely does their action approach to that of a vacuum.

If, instead of comparing the gases at a common pressure of the atmosphere, they are compared at a common pressure of an inch, we find the following comparative effects:—

Name of gas	Relative absorption at 1 inch pressure
Air	1
Oxygen	1
Nitrogen	1
Hydrogen	1

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Name of gas	Relative absorption at 1 inch pressure
Chlorine	60
Bromine	160
Carbonic oxide	750
Carbonic anhydride	972
Hydrobromic acid gas	1005
Nitric oxide	1590
Nitrous oxide	1860
Sulphide of hydrogen	2100
Ammonia	5460
Olefiant gas	6030
Sulphurous anhydride	6480

Thus for every ray intercepted by air, oxygen, hydrogen, or nitrogen, ammonia intercepts 5460, olefiant gas 6030, while sulphurous anhydride destroys 6480. Thus these experiments disclose extraordinary differences in the constitution and character of the molecules of various gases.

292. **Action of vapours.**—If flasks containing liquids, purified from air, be attached to the experimental tube, the behaviour of vapours of various liquids can be investigated. The results are given in the following table for a pressure of 0·1, 0·5, and 1 inch :—

Name of Vapour	Absorption at the pressure		
	0·1 inch	0·5 inch	1·0 inch
Bisulphide of carbon	15	47	62
Iodide of methyl	35	147	242
Benzole	66	182	267
Chloroform	85	182	236
Methylic alcohol	109	390	590
Amylene	182	535	823
Sulphuric ether	300	710	870
Alcohol	325	622	
Formic ether	480	870	1075
Acetic ether	590	980	1195
Propionate of ethyl	596	970	
Boracic ether	620		

These numbers refer to the absorption of a whole atmosphere of dry air as their unit; that is to say, bisulphide of carbon vapour at 1-10th of an inch pressure absorbs 15 times more than the atmospheric air at a pressure of 30 inches. The vapour of boracic ether, at 1-10th of an inch pressure, produces 620

times the effect that is produced by air at 30 inches pressure, and so on. Comparing air and boracic ether vapour at the same pressures, the absorption of the latter is probably more than 180,000 times that of the former.

293. **Action of perfumes.**—Of high interest is the absorptive action of scents and effluvia. To experiment upon them a number of small and equal squares of bibulous paper are rolled up so as to form little cylinders, each about two inches in length. Each paper cylinder is then moistened by dipping one end of it into an aromatic oil; the oil creeps by capillary attraction through the paper until the whole of the roll becomes moist. The roll is introduced into a glass tube of a diameter which enables the paper cylinder to fill it without being squeezed; the tube containing the paper is connected with the experimental tube, dry air is caused to pass through it, and the air takes up the perfume of the aromatic oil and carries it forward into the experimental tube.

Taking the absorption of one atmosphere of dry air to be unity, the following table gives a condensed view of the results:—

Name of Perfume.	Absorption.
Patchouli	30
Sandal wood	32
Geranium	33
Oil of cloves	34
Otto of roses	37
Bergamot	44
Neroli	47
Lavender	60
Lemon	65
Portugal	67
Thyme	68
Rosemary	74
Oil of laurel	80
Camomile flowers	87
Cassia	109
Spikenard	355
Aniseed	372

In addition experiments were made on aromatic herbs, with the following result:—

Herbs.	Absorption.
Thyme	33
Peppermint	34
Spearmint	38
Lavender	32
Wormwood	41
Cinnamon	53

294. **Absorption of aqueous vapour.**—The most important results obtained by Professor Tyndall refer to the absorption of aqueous vapour. When the experimental tube is filled with perfectly dry air the absorption exercised by it is taken as one unit. If now the tube is exhausted, and air allowed to enter from the laboratory, not specially moist, the absorption rises to 72 units, a difference which must be due to the aqueous vapour in the air. Analogous results were obtained on different days, and with specimens of air taken from different localities. Dry air passed through a tube filled with fragments of moistened glass and examined gave, after reception of the vapour, an absorption 90 times that of pure air.

These results are of great importance to meteorological science. That 10 per cent. of the entire terrestrial radiation is absorbed by the aqueous vapour which exists within ten feet of the earth's surface on a day of average humidity is a moderate estimate. In warm weather and air approaching to saturation the absorption would probably be considered greater. This single fact at once proves the importance of the action of vapour on radiant heat as regards meteorology. Vapour which absorbs heat so greedily must radiate it copiously. This fact must come powerfully into play in the tropical regions of calms, where enormous quantities of vapour are raised by the sea, and discharged in torrents upon the earth. These have been assigned to the chilling consequent on the rarefaction of the ascending air. But if we consider the amount of heat liberated in the formation of those falling torrents, the chilling due to rarefaction will hardly account for the entire precipitation. The substance quits the earth as vapour, it returns to it as water; hence the question arises, how has the latent heat of the vapour been disposed of? It is a fair inference, drawn by Professor Tyndall, that it has in great part been radiated into space. But the radiation which disposes of such enormous quantities of heat subsequent to condensation is competent, in some measure at least, to dispose of the heat possessed prior to condensation, and must, therefore, hasten the return of condensation itself. Aqueous vapour is a powerful radiant, but it is an equally powerful absorbent, and its absorbent power is at a maximum when the body which radiates into it is vapour like itself. Hence when the vapour first quits the equatorial ocean and ascends it finds for a time above it a screen of its own substance, into which it passes its heat, and by which that heat is intercepted and returned. Condensation in the lower regions of the atmosphere is thereby prevented. But as the mist ascends it passes through

successive vapour-strata until finally the ascending body of vapour finds itself lifted above the screen which for a time protected it. It now radiates freely into space, and condensation is the consequence.

This is only one instance how the knowledge of the absorptive power of vapour may solve many difficulties in meteorology, and how many familiar effects may have a novel interest attached to them, by recognising their connexion with the action of vapour on radiant heat.

295. Summary of the preceding phenomena of radiant heat.—1. *Emission*.—Each body radiates at each temperature heat, and receives heat at each temperature; if more is received than radiated, the temperature rises, and *vice versa*; if as much is radiated as received, the temperature remains constant, and we have Prevost's *moveable equilibrium*.

The vibrating molecules act upon the ether, and the vibrating ether upon the molecules; hence a continual exchange of movements, which leads to the moveable equilibrium. That bodies emit heat at every temperature is shown thus: A thermometer at an ordinary temperature placed near ice at -5° falls, because it radiates more heat than it receives; but if placed in a room at -10° it will rise if a piece of ice at -5° is brought near it, because it receives more heat from it than it radiates. Similarly, the needle of a galvanometer is deflected in one direction by a colder, in the other direction by a warmer body, if the instrument had in each case its needle at zero. As another example, the radiation of the soil in hot countries into space produces a very considerable cooling of the surface.

In general the term *emission* is applied to the case when a body radiates more than it receives.

Absorption, again, denotes the case when more heat is received than radiated. In this sense, emission takes place when the body has a higher temperature than surrounding objects, absorption when the conditions are the reverse. That absorption is equal to the emission at the same temperature, other circumstances being the same, follows at once from Prevost's theory of exchange, and the moveable equilibrium. It is in fact only a special case of Kirchhoff's law of absorption of light, which may be thus enunciated: The absorptive power of every substance for rays of a definite wave-length is equal to its emissive power for rays of the same wave-length. As regards light, an immediate consequence of this law is that a non-luminous, or faintly luminous, body absorbs the same colour which it emits when in a self-luminous state. This fact had been

experimentally determined long before Kirchhoff's enunciation of the general law, by Professor *Balfour Stewart*. The experiment described in Art. 287 is one of those made by this distinguished physicist for proving the law also for thermal rays.

The consequences of the law are very important; because the emission cannot be well measured, while the absorption is more easily ascertained by suitable experiments.

The emission increases with the difference of temperature of body and surrounding locality, but is not proportional to this difference. The deviation from this proportionality is very different. The quantity of heat emitted depends on the nature of the body; it is least in metals, greater in organic bodies, greatest in lampblack. It depends on the nature of surface; loose, porous, soft, dark, rough surfaces radiate more than polished, hard, bright surfaces; scratched metals more than polished. Emission depends also on the nature of the surrounding medium. It seems independent of the state of aggregation.

The *kind* of heat is also to be considered. The kind depends on the number of vibrations per second. Rays below 400 billions are dark and warm; between 400 and 500, red and yellow, and warm; hence the colour of heat rays is spoken of, meaning only the difference in the number of vibrations. In the solar spectrum rays of low numbers are mixed with high. In luminous platinum the heat spectrum has a long dark space while the luminous is small, the former as large as in the spectrum of the sun. Rock-salt emits at 150° only one heat colour (rays of one number of vibrations); it is *monothermic*. Sylvin (K Cl) is nearly monothermic. Other bodies radiate at 150° heat of various colours. At a red heat (400 billions) the temperature of all bodies is 500° at any rate (all bodies are then red hot).

Bodies cool by emission. The velocity of cooling is the diminution of temperature per minute. The velocity is subject to definite conditions (the *law of cooling*), which were for some time considered rather simple. *Newton* thought the velocity proportional to the difference of temperature. *Dulong* and *Petit* have shown that, if the difference is equal, the velocity is at a higher temperature greater than at a lower. The nature of the body, its specific heat, the magnitude and emissive power of its surface, the conductivity of the surrounding locality, and other influences render the law complex.

Relative emission from Leslie's experiments: Lampblack, 100; paper, 98; resin, 96; sealing-wax, 95; crown glass, 90; ice, 85; mica, 80; graphite, 75; rough lead, 45; mercury, 20; polished lead, 19; gold, silver, copper, tin, 12.

According to Melloni: white lead, 100. (Silver, when scratched, 18; polished and hammered, 10.) Polished, molten, 14; molten, scratched, 11.

Hot water pipes should hence be polished. Stoves should be covered with lampblack.

Franklin's experiment: Dark rags on snow sink deeper, hence greater absorption and greater emission. Tyndall covered Leslie's cube with differently coloured velvet, and also with layers of different colours—emissions were not different. Hence Franklin's result erroneous.

Tyndall found that elementary gases radiate very little; more so CO , CO_2 , carbonic oxide, and carbonic anhydride.

Vapour of water has a great emissive power. Liquids range themselves like their gases or vapours.

Heat is propagated by radiation in all directions, in straight lines in the same medium, and diminishes as the square of the distance.

Proofs: A thermopile shows the same deflection all round a radiating body. If a screen is interposed, the needle turns back again. When a screen is heated and removed 2, 3, 4 times the first distance, we observe the same deflection, but as the surface is 4, 9, 16 times greater, each unit gives out $\frac{1}{4}$, $\frac{1}{9}$, $\frac{1}{16}$ of the heat, which proves the law. Leslie's differential thermometer is useless for this experiment, because of the diminished inclination of the rays when the instrument is further removed from the source of heat.

296. **Reflexion and refraction of heat.**—Heat is absorbed, regularly reflected, irregularly reflected, transmitted, and refracted.

Regular reflection may be shown by Melloni's apparatus. Similarly refraction. The laws of reflection are further proved by concave reflectors; those of refraction by burning-glasses. White lead produces much irregular reflection, lampblack not. White bodies diffuse luminous rays better than dark rays. Dark bodies diffuse little of all rays. Metals diffuse all rays equally well. Metals behave with reference to heat like white bodies with reference to light.

297. **Refrangibility of different kinds of heat rays.**—Rays of different temperature, of different sources, and different rays from the same source have a different refrangibility, like different colours of light. Dark heat rays of low temperature have the least refrangibility. Heat rays of luminous hot bodies are more refrangible, and the refrangibility increases with the luminosity of the heat.

The difference arises from the fact that the different kinds of heat rays have a different number of vibrations. Rays from a hot sheet of copper exhibit the least refrangibility, the hot platinum spiral more, Locatelli's lamp the greatest. The latter gave out rays of different refrangibility. *Forbes* determined the indices of refraction by finding the limiting angle of total reflection (whose sine = index of refraction). A rocksalt prism had to be used, because it transmits all heat rays. Most heat emitted was found to be a mixture of different kinds. Rocksalt alone proved an exception.

298. **Absorption.**—If the vibrations of ether enter a body, a part is converted into molecular motion, the ether atoms communicating their own vibrations to the atoms of the body. The heat rays are then *absorbed*, and go to heat the body sensibly. Those rays only are absorbed of which the vibrations agree with the molecular vibrations of the body; the remainder remain ether vibrations, and pass out of the body.

Absorption is equal to emission. It is slight in polished, well reflecting, well diffusing bodies. In metals it is the least; lampblack has the greatest absorption. Absorption differs with the kind of heat. Lampblack absorbs all rays. White lead absorbs preferably dark heat rays, little luminous. Metals absorb all kinds of thermal rays equally badly. Colourless transparent bodies absorb mostly dark heat rays, coloured absorb heat rays of different colour. Elementary gases absorb little, aqueous vapour more, and compound gases still more.

Melloni used a sheet of copper, one side covered with lampblack, as a source of heat; the other side covered with the body under investigation was turned towards the thermopile.

Melloni's results are the following. The absorption of lampblack is equal for all heat rays. Denoting it by 100, that of white lead for rays from the lamp is 53, for glowing platinum 56, for copper at 400° 89, for copper at 100° 100.

Bodies differ for the same heat. The same body differs for different heat.

De la Provostaye and Desains denote the absorption of lampblack = 1. Then that of steel for rays of the sun = .42. For Argand's lamp, .34. For Locatelli's lamp, 0.175.

Platinum, .39, .30, .17, for the same three sources.

Tyndall enclosed gases and vapours in long tubes, closed by rocksalt discs. At one side the source of heat, at the other the thermopile. A method of compensation consisted in another source of heat on the other side of the thermopile.

If absorption of air or elementary gases at 1'' pressure = 1 ;

Chlorine = 60; nitrous oxide, 1590; SH_2 , 2000; NH_3 , 7260; SO_2 , 8800. Several successive tubes diminish the sum total of absorption, that is, the effect of their sum is less than the sum of the single effects. Acetic ether, 1195. Perfumes 370 greater than air. Ozone from 30 to 136 times that of oxygen. Vapour of water absorbs about 10 per cent. of the radiated heat of a source of heat on a dry day. Magnus, on the other hand, found that moist air has no greater absorption than dry.

Liquids, enclosed in a cell of rocksalt. Source of heat a platinum wire made hot by a constant current. The absorption increases with the thickness of the layer, first rapidly, then slowly.

Layer of water, 0.02"	80.7 per cent.	Alcohol, 67 per cent.
" " 0.04	86.0	"
" " 0.07	88.8	"
" " 0.14	91.0	"
" " 0.27	91.0	"

Water greatest, then alcohol, then ethers, then S_2C .

Absorption of vapours in the same order.

The more luminous the source of heat, the greater the absorption from it.

Platinum luridly glowing, S_2C , 6.5

" red hot,	4.7	white hot,	2.9
Leslie's tube, 6.6	gas, 9.8	Bunsen's lime,	6.2

Since transparent bodies, as seen from the first numbers, absorb more dark heat, it follows that a gas flame contains much dark heat.

299. **General results.**—There are thus, as regards thermal radiation, bodies which are *diathermane* and such as are *adiathermane*. *Thermochroic* bodies transmit only a certain kind of heat rays. Diathermaney is now used to denote the general capacity for transmission of heat, diathermancy or thermochrosis that for transmitting only certain kinds of rays.

Transparent bodies transmit mostly luminous heat, but weaken dark heat. Rocksalt and Sylvite are exceptions, transmitting all, with exception of the few which they absorb. Opaque bodies stop luminous heat, but a few in thin layers, as, lamp-black, black mica, black glass, iodine dissolved in disulphide of carbon, S_2C , transmit dark heat. Coloured transparent bodies are only diathermane for heat of their own colour. Dry elementary gases are more diathermane than rocksalt, other gases or vapours stop certain rays.

Rays passed through ice, previously through water, do not melt the ice.

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Absorption takes place mostly in the superficial layers of a body; beyond a certain limit it ceases, and the bundle of rays remains afterwards unaltered, and passes without loss even through a second plate.

Hence generally,—(1.) Heat of each source has different heat rays.

(2.) Luminous sources emit also mostly dark rays.

(3.) After transmission the kind of heat is different; it is that of the substance which transmits.

(4.) Transparent bodies (except rocksalt) absorb dark rays pre-eminently, transmit luminous.

(5.) Sources of low temperature emit only rays of low refrangibility.

(6.) The number of dark rays increases with the temperature, but also the luminous rays increase, or their refrangibility increases. Ice is most adiathermane.

Different heat rays suffer also unequal reflection. When heat from Locatelli's lamp has passed through glass or rocksalt, different quantities are reflected by speculum metal, silver, and platinum. Fluorspar reflects 30 per cent. of heat emitted from heated rocksalt, but only 6 to 10 per cent. from other sources. Silver reflects from 83 to 90 per cent. of heat emitted by other sources of heat, glass 6—14, fluorspar 6—10 per cent. The latter substance reflects of heat emitted by Sylvan 15—17 per cent.

CHAPTER XIV.

THE DYNAMICAL THEORY OF HEAT.

300. **Heat is a kind of Motion.**—It has long been accepted by scientific men that motion and heat were so intimately connected as to be equivalent, varying in form but being the same in nature, and easily convertible from one form to the other, without waste or destruction of even the smallest portion of the energy. To demonstrate this by exact experiment beyond a shadow of doubt, has, however, taken up much time, and required the greatest care and abilities on the part of the experimenter.

There are many illustrations presented by the common occurrences of life which prove that heat is a form of motion, or rather that that kind of motion called heat is always developed when the ordinary form of the motion of a body is suddenly checked or gradually diminished, as for example, by friction. We may call to mind the savage taking up two pieces of dry wood, rubbing them together, and obtaining fire. Again, when the brake is put on a railway carriage, the friction of the wheel on the rail throws off fire in the form of clouds of sparks. Our own bodies may be said to be constantly renewed by the application of heat, which is expended in motion, and it is well known that an extra amount of motion or expenditure of heat results in an extra call for supply of heat-giving materials to the body. A leaden bullet is placed on an anvil and struck with a sledge hammer; the amount of heat generated by percussion is sufficient to raise the temperature of the bullet, and if the heat generated could be collected without loss we should be able, by means of it, to raise the hammer to the height from which it fell. *In all cases where mechanical force is expended in producing heat, or the converse takes place, the relation between the two may be expressed by an equivalent of heat and work.*

301. **Joule's Experiments.**—Joule's experiments for determining this equivalent were made upon the friction of water, mercury, and cast iron. The apparatus employed for the experiments upon water consisted of a brass paddle-wheel, furnished with eight sets of revolving vanes. This revolving apparatus was firmly fitted into a copper vessel containing water, in the lid of which were two necks, one for the axis to revolve in without touching, the other for the insertion of a thermometer. Motion was given to the axis by the descent of leaden weights, suspended by strings from the axes of two wooden pulleys, their axes being supported on friction wheels, and the pulleys were connected by fine twine with a wooden roller, which, by means of a pin, could be easily attached to or removed from the friction apparatus. The mode of experimenting was as follows:—The temperature of the friction-apparatus having been ascertained, and the weights wound up, the roller was fixed to the axis, and the precise height of the weights ascertained; the roller was then set at liberty, and allowed to revolve till the weights touched the floor. The roller was then detached, the weights wound up again, and the friction renewed. This having been repeated twenty times, the experiment was concluded with another observation of the temperature of the apparatus. The mean temperature of the apartment was ascertained by observations made at the beginning, middle, and

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end of each experiment. Corrections were made for the effects of radiation and conduction, and in the experiments with water for the quantities of heat absorbed by the copper vessel and the paddle-wheel. In the experiments with mercury and cast-iron, the heat-capacity of the entire apparatus was ascertained by observing the heating effect which it produced on a known quantity of water in which it was immersed. In all the experiments corrections were also made for the velocity with which the weights came to the ground, and for the friction and rigidity of the strings. The thermometers used were capable of indicating a variation of temperature as small as $\frac{1}{200}$ of a degree Fahrenheit.

The following table contains a summary of the results :—

Materials employed	Equivalent in air	Equivalent in vacuo	Mean
Water . . .	773·640	772·692	772·692
Mercury . . . {	773·762	772·814	774·083
	776·303	775·352	
Cast Iron . . . {	776·997	776·045	774·987
	774·880	774·930	

The number 772·692, obtained by the friction of water, is regarded as the most trustworthy.

The conclusions deduced from these experiments are—

1. That the quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the force expended.

2. That the quantity of heat capable of increasing the temperature of 1 lb. of water (weighed in vacuo and between 50° and 60°) by 1° Fahrenheit, requires for its evolution the expenditure of a mechanical force represented by the fall of 772 lbs. through the space of 1 foot.

Or, the heat capable of increasing the temperature of 1 kilogramme of water by 1° C, is equivalent to a force represented by the fall of 423·55 kilogrammes through the space of 1 metre.

This is consequently the mechanical equivalent of a unit of heat.

302. **Heat rendered sensible by compression of air.**—For determining the heat produced by the compression of a gas, like air, Joule used a copper vessel, 12 inches long, $\frac{1}{4}$ inch thickness of wall, and 136 $\frac{1}{2}$ cubic inches contents. The air in it was com-

pressed to a pressure of about 22 atmospheres by a condensing pump attached to it. The whole, pump and all, was immersed in 45 lbs. 3 oz. of water. 300 strokes of the piston brought the pressure to 21·654 atmospheres; the temperature of the water rose $\cdot643^{\circ}$ F. Part of this heat is due to the friction. The entrance of the air from outside was now excluded, and 300 strokes pro-

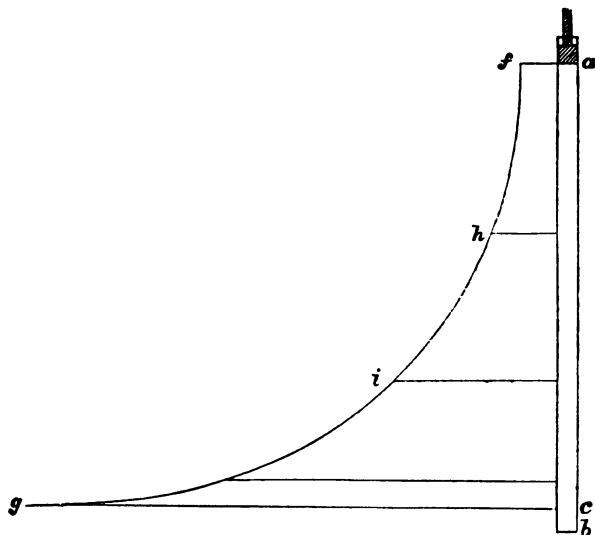


Fig. 108.

duced a heating effect of $\cdot297^{\circ}$ F. Hence, rise of temperature due to compression = $\cdot643 - \cdot297 = \cdot346^{\circ}$ F.

Since $136\cdot5 \times 21\cdot654 = 2,956$ cubic inches of air are compressed into a space of 136·5 cubic inches, it appears from this experiment, after applying the necessary corrections, that the heat thus set free would heat 1 lb. of water by $13^{\circ}628$ F., or 3·437 kilogrammes 1° C.

To find the mechanical labour required to compress 2,956 cubic inches to 21·654 times their density, let the air be supposed to be in a tube, *a b fig. 108*, 21·654 feet long, and let its section be 11·376 square inches; thus one foot length of tube will exactly be equal in volume to the contents of the vessel, since $12 \times 11\cdot376 = 136\cdot5$. Now, let the piston be pushed down to a foot from the ground, that is, from *a* to *c*, then the air in the

tube which originally filled a space represented by 21·654 units, will be compressed into the $\frac{1}{21\cdot654}$ th part of its original volume, and its density, also its pressure, will then be equal to that in the vessel used in the experiment. Let now, at various points of the tube, lines be drawn at right angles to it, so that their length is always proportional to the pressure of the enclosed air, when the piston has reached that point, the line $c g$ being, on that supposition, 21·654 times longer than $a f$; if the pressures be thus represented by these lines, then the area enclosed by the curve (hyperbola) $f h i g$ and the tube $a c$ represents the force required for pushing the piston from a to c . Let $g c$ be denoted by y , $b c$ by x , and $b a$ by x' ; then the area =

$$H = xy \log. \text{nat. } \frac{x'}{x}$$

and if $x = 1$

$$H = y \log. \text{nat. } \frac{x'}{x} = 2\cdot3026 y \log. x' \text{ if } \log x' \text{ is calcu-}$$

lated by ordinary logarithms.

At the experiment the barometer stood at 30·2 inches, hence the pressure upon a section of the tube is 168·5 lbs.

$$\begin{aligned} \therefore fa &= 168\cdot5, \\ gc &= 21\cdot654 \times 168\cdot5 = 3648\cdot7 \\ x' &= 21\cdot654 \end{aligned}$$

$\therefore H = 2\cdot3026 \times 3648\cdot7 \log. 21\cdot654 = 11220$ footpounds, being the work required for the compression of 2956 cubic inches to $\frac{1}{21\cdot654}$ of the space, and this produced 3·437 units of heat. But 1552 kilogrammetres = 11220 footpounds.

\therefore mechanical equivalent from this experiment = 451 kilogrammetres.

When the air is allowed to flow out of the vessel in which it was compressed, the same heat was found to be required, if the resistance of the air is to be overcome, that was generated by the compression. But when another vacuous vessel is attached to it, no heat is required, for no work is done.

303. **Hirn's Experiment.**—A cylinder of wrought-iron is suspended by two strings. The weight of the cylinder is 350 kilogrammes. A block of sandstone, weighing 941 kilogrammes, with a plate of iron, is opposite to it. Between the block and cylinder is a small cylinder of lead, weighing 2·948 kilogrammes, which is partly hollow for inserting a thermometer. At the beginning of the experiment the temperature of the lead cylinder

is $7^{\circ}87$. Let now the iron cylinder be raised and allowed to strike upon the lead.

Then let the following be the observed data of the experiment :

Height of fall of cylinder $1\cdot166$ metres.

After impact, back again $0\cdot087$ „

Height of ascent of block after impact $0\cdot103$ „

Hence, *work* of hammer $350 \times 1\cdot166$ kilogrammetres,
 $= 408\cdot100$.

Work of rebounding parts,

$0\cdot103 (941 + 2\cdot95) + 0\cdot087 \times 350 = 127\cdot677$.

Difference $280\cdot423$ kilogrammetres.

We have now to find the quantity of heat produced by this mechanical work.

In the cavity of the lead cylinder, $18\cdot5$ grammes of water at 0° were poured ; 4 minutes after impact the temperature was $12^{\circ}\cdot10$

8 „ „ „ „ „ $11^{\circ}\cdot75$
 \therefore cooling in 4 minutes $0^{\circ}\cdot35$

cooling during first 4 minutes follows from the
 proportion, $11\cdot75 : 12\cdot10 :: 35 : x = \cdot36$

Temperature at the moment of collision,

$$12\cdot10 + \cdot36 = 12^{\circ}\cdot46$$

Hence rise of temperature due to impact, $12\cdot46 - 7\cdot87 = 4^{\circ}\cdot59$

Units of heat produced, taking $0\cdot03145$ as the specific heat of lead,

$$4\cdot59 \times 2\cdot948 \times 0\cdot03145 + 12\cdot46 \times \cdot00185 \\ = \cdot656 \text{ units}$$

The proportion $\cdot656 : 1 :: 280\cdot423 : 427$

gives thus 427 kilogrammetres as the equivalent found from this experiment.

304. Specific Heat of Air at constant Volume and constant Pressure.—Let a quantity of air be enclosed in a cylinder with a moveable piston, and heated until the volume is doubled. Then since the density of the air is $\frac{1}{773}$ that of water, and one litre of water at 0° may be taken to weigh one kilogramme, the heat required is $\frac{24 \times 273}{773}$ if $\cdot24$ is the specific heat of air at constant pressure, if the cylinder has an area of $10 \square^{\text{cm}}$, and the volume of the air is exactly 1 litre. If the piston had

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been fixed, and the temperature raised by 273° , then only $\frac{100}{142}$ of this heat would have been required. The surplus was previously required because the air did work in the first case, namely, to raise a pressure of 760^{mm} upon $10 \square^{\circ}$ through 1^{m} . The surplus is the mechanical equivalent of heat, it is—

$$\frac{42}{142} \times \frac{0.24 \cdot 273}{773} \dots \dots \dots (A)$$

$$\text{The work done is } \frac{10 \times 76 \times 13.6}{1000} \text{ kilogrammetres (B)}$$

$$A : B :: 1 : 412 \text{ kilogrammetres.}$$

Or we may consider the subject thus: one cubic metre of air at 0° and atmospheric pressure, or 1.293 kilogrammes of air, must be heated from 0° to 273° , so that its tension may be two atmospheres.

This requires $273 \times 1.293 \times 0.1686$ units = 59 , because $.1686$ is the specific heat of air at constant volume.

But if one cubic metre of air at 0° is heated to 273 , while it can expand, its volume will be twice what it was before, and the heat required is

$$273 \times 1.293 \times .2377 = 83 \text{ units}$$

$.2377$ being the specific heat at constant pressure, both specific heats being determined by independent experiments.

The difference = $83 - 59 = 24$ represents the thermal units required for the expansion.

To calculate the work, suppose the air to fill a vessel of a square metre base, and one metre high, below a piston. The pressure of the atmosphere upon this piston is 10333 kilogrammes, and to raise the piston one metre 10333 kilogrammetres of work are required, and 24 units of heat.

$$\text{Hence } \frac{10333}{24} = 430 \text{ kilogrammetres} \\ = \text{equivalent.}$$

Here heat has produced a mechanical effect, while in the preceding experiments mechanical work was converted into heat.

305. Further consequences and theoretical considerations.—Considering heat as molecular motion, we may, from the preceding facts, derive the following statements. 1. The temperature of a body is proportional to the *vis viva* of the molecules. Increase of temperature is increase of the *vis viva*.

Not all heat conveyed into a body is employed in increasing

the *vis viva*, for a portion may be employed to equilibrate molecular forces which act between the molecules and prevent the free motion. This is latent heat = L . If sensible heat = T , then total heat in the body $U = T + L$.

2. If a body has temperature t , volume v , and is to be raised to volume $v + v'$, temperature $t + t'$, and the heat in the body $U + U'$, then U' is insufficient for the purpose, because the volume having increased, *external* work has been done.

If p = pressure upon the body, then the external work required for increasing the volume by v' is $p v'$ if the pressure during expansion is constant; the heat corresponding to this work required is: Heat = $w = \Delta p v'$ ($\Delta = \frac{1}{424}$). Hence heat required for raising the temperature to $t + t'$, volume to $v + v'$, heat contained to $U + U'$ is

$$Q = U' + \Delta p v' \quad \dots \dots \dots (I)$$

$$\text{or } dQ = dU + \Delta p dv \quad \left(\begin{array}{l} dQ = \text{increment of heat to be added} \\ dU = \text{increment of heat contained,} \\ \text{so that the volume has an increase of} \\ dv. \end{array} \right) \quad (Ia)$$

The equation (I) or a corresponding one is the mathematical expression of the *first law of Thermodynamics*. It enables us to calculate the heat which disappears, with change of volume, when a body is under a known pressure, and the work done by expansion is known, which is only the case when only external work is involved; internal work cannot be directly measured. This is only the case with *perfectly gaseous* bodies. The following is an example of the application of this law. A hollow cylinder, *fig.* 109. $1 \square^m$ section, contains air 1^m high. Hence one cubic metre of air, reaching to piston κ ; the air is at 0° . The pressure upon it is 10333 kilogrammes. This air heated to 273° , expands to double the volume; the piston rises to κ' . The work done is 10333 kilogrammetres, and the heat consumed

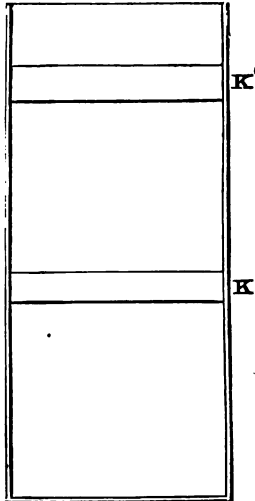


Fig. 109.

$$\Delta p v' = \frac{10333}{424} = 24.37 \text{ units.}$$

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The total heat which must be conveyed to a cubic metre of air at 0° and atmospheric pressure (1293 kilogrammes) to heat it to 273° is, when the pressure is constant,

$$273 \times 1.293 \times 0.2377 = 83 \text{ units.}$$

$$\therefore 83 = v' + 24.37$$

$$v = 58.63$$

\therefore 58.63 units pass into the air, 24.37 perform the work of expansion. Only 58.63 units are, therefore, required for heating solely air from 0° to 273° , if the volume remains constant, or

Specific heat at constant pressure : specific heat at constant volume :: 83 : 58.63

$$1.415 : 1$$

or better 1.421 : 1 as found in a different manner in art. 242, page 317.

In this calculation the mechanical equivalent of heat is supposed to be known.

In the following example the law is applied to steam.

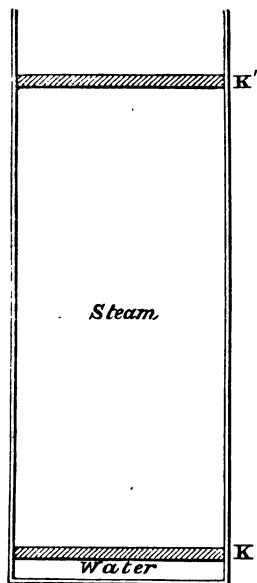


Fig. 110.

The cylinder, *fig. 110*, has a section of one square metre. There is one litre of water in it at 0° . The pressure p upon the piston is that of saturated vapour at t° . Let the water be heated to t° , and let the expansion be neglected. The heat required is $= t + .00002t^2 + .0000003t^3 = w$, if the change of the specific heat with the temperature is considered, or t , when specific heat = 1. The unit being the heat required for raising one kilogramme, that is, in this case one litre to 1° . No steam can yet be formed. If more heat is introduced, steam is formed of tension p . The piston moves upwards until all water is steam. Let the heat required for the formation of steam at t° be r (at constant pressure). This is usually called the latent heat. The total heat is under these suppositions

$$Q = w + r$$

But $q = 606 + \cdot 305t$ (art. 190, page 225)

$$\therefore r = 606 \cdot 5 - \cdot 695 t - \cdot 00002 t^2$$

$$- \cdot 0000003 t^3,$$

$$\text{or} = 607 - 0 \cdot 708 t.$$

Hence, if r were exclusively employed for external work, $r = \Delta pu$, and it would be easy to calculate the volume of the steam formed, for then u could be calculated, that is the space $\kappa\kappa'$ which is filled, when the kilogramme of water at t° becomes steam at t° . But r consists of two portions. Δpu performs the external work pu , while another portion, ρ , works again *cohesion*.

$$\therefore r = \rho + \Delta pu.$$

We know neither ρ , nor Δpu , nor their mutual relation; in order to determine these quantities, ρ must be eliminated by performing with the steam a definite external work, at the end of which the internal work = 0. This process is called in the theory of heat a cycle.

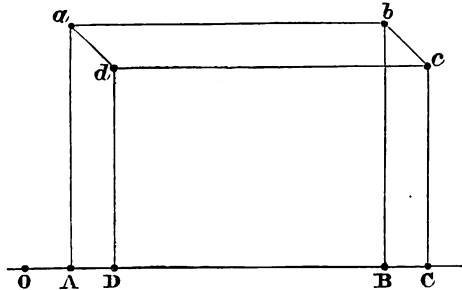


Fig. III.

Let w = volume of unit of weight of water at $t^\circ = 0$ A, fig. III,
 $p = Aa$.

If steam is formed by heat, the steam having the same temperature t , then p is constant. Let all water be evaporated. Then w becomes v , = OB, that is, the increase = $u = AB$, and the work done is $ABab = pu$. The heat conveyed to it is r .

Let this steam now expand without the addition of heat until the temperature falls 1° , and the tension is reduced by ϕ , OB becomes OC. Then the work $d = BCbc$, and q = the heat lost.

Temperature of the steam $t - 1$.
 pressure $p' = p - \phi$. } under these circumstances.

Let it be compressed, by the volume u , that is, by C D in the figure, being at the same temperature, but losing

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heat, the tension remaining $p - \phi$. Then r' , the heat, becoming sensible and withdrawn from the steam, consists, first, of $\Delta p'u$, corresponding to the work $p'u$ expended in compressing, represented by $cbdc$; and, secondly, ρ' , which becomes free by condensation. If now the compression is continued from od to oa , the temperature becomes t° , the pressure p , and the steam becomes water at its original temperature t . The work done is $d = pdaA$, and the heat q is again conveyed into the body which it had lost in expanding from ob to oc .

During this cycle the heat r and q did first $pu + d$ work, while the work $p'u + d$ produced $r' + q$ heat.

\therefore The sum of the work gained = $pu + d - p'u - d = qu$, represented by the parallelogram $abcd$.

The heat required for this work is $r + q - r' - q = r - r'$. But the work qu requires Δpu heat $\therefore \Delta u = r - r'$. Hence r' is to be determined to find u . Without applying the calculus, we may proceed approximately thus.

The quantities of heat are proportional to the tensions or:—
 $\Delta pu : \Delta p'u :: p : p' :: \text{density of vapour at } t^\circ : \text{density at } (t-1)$.

Proportional to these densities are the quantities of water which evaporate at t while expanding through u , and at $(t-1)^\circ$ while being compressed through u .

$$\begin{aligned} \therefore \rho : \rho' :: p : p' \\ \rho + \Delta pu : \rho' + \Delta p'u :: p : p' \\ r : r' :: p : p', \\ \text{but } p : p' :: 1 + \alpha t : 1 + \alpha(t-1) \\ \therefore r : r' = (1 + \alpha t) : 1 + \alpha(t-1) \\ r' = r \frac{1 + \alpha(t-1)}{1 + \alpha t} \end{aligned}$$

$$\begin{aligned} r - r' &= r \left(1 - \frac{1 + \alpha(t-1)}{1 + \alpha t} \right) \\ &= \frac{r\alpha}{1 + \alpha t} \end{aligned}$$

dividing by α , and putting $\frac{1}{\alpha} = a$

$$r - r' = \frac{r}{a + t} = \frac{r}{T}, T = \text{absolute temperature corresponding to } t.$$

$$\therefore \Delta u = \frac{r}{T}$$

$$u = \frac{r}{\Delta T} \quad u = \frac{424r}{T\rho} \quad . \quad . \quad . \quad (II)$$

or for every temperature u can be determined. The equation (II) is generally called the *second law of thermodynamics*.

306. **Steam Engines.—Loss of Heat when work is done.**—Hirn showed the loss of heat when work is done by steam-engines, in which the steam passed into a condenser after performing work. To prevent errors from various mechanical sources the steam was superheated, before entering into the cylinder, and its temperature previously ascertained.

The quantity of water evaporated per second (p) was carefully determined, and the water which was thrown by the jet into the condenser (P) was also found per second from measurements of the water used for condensation during a whole day.

The heat given up by the condensed vapour is found thus : Let t be the temperature of the vapour when formed in the boiler, then the heat which it contains in one kilogramme more than that in one kilogramme of water at 0° is :

$$q_1 = 606.5 + 0.305t \text{ units.}$$

This vapour is heated to τ before entering the cylinder, and if 0.5 = the specific heat of vapour, it requires for each kilogramme,

$$q_2 = 0.5 (\tau - t) \text{ units.}$$

If this kilogramme is condensed and cooled to a temperature of f° , with which the water leaves the condenser, the heat lost by it is

$$q_1 + q_2 - f,$$

and the heat which in each second is given off by the weight p of steam passing per second through the engine is thus :

$$\begin{aligned} Q^1 &= p_1(q + q_2 - f), \\ &= p(605.5 + 0.305t + 0.5(\tau - t) - f). \end{aligned}$$

Suppose that no heat is lost for work done, then this heat is used for heating the water entering the condenser, and if this water has a temperature i when entering, and f when leaving the condenser,

$$P(f - i) = Q_2$$

should be equal to Q_1 . But experiment proves that this is not the case, as shown by the following individual experiments.

First experiment. The pressure of the steam was 4.5 atmospheres, hence

$$\begin{array}{lll} t = 148.3 & p = 0.34554 \text{ kilos.} & f = 37.28 \\ \tau - t = 91.7 & P = 5.84004 \text{ kilos.} & i = 5.1. \end{array}$$

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$$\begin{aligned}\text{Hence } Q_1 &= 228 \cdot 16 & Q_2 &= 187 \cdot 82 \\ Q_1 - Q_2 &= 40 \cdot 34 \text{ units.}\end{aligned}$$

The useful effect of the machine was 11250 metre-kilogrammes,

$$\begin{aligned}\text{hence one unit gives } \frac{11250}{40 \cdot 34} &\text{ as useful effect.} \\ &= 278 \text{ metre-kilogrammes.}\end{aligned}$$

In another experiment

$$\begin{aligned}t &= 152^\circ 2 & p &= 0 \cdot 23548 \text{ kilos.} & f &= 26 \cdot 05 \\ T - t &= 93^\circ & P &= 5 \cdot 8718 \text{ kilos.} & i &= 3 \cdot 2 \\ Q_1 - Q_2 &= 158 \cdot 81 - 123 \cdot 3 = 35 \cdot 51 \text{ units.}\end{aligned}$$

The useful effect was 8700 :

$$\therefore \frac{8700}{35 \cdot 51} = 245 \text{ metre-kilogrammes.}$$

or the useful effect is proportional to the loss of heat.

If the useful effect is 70 per cent., then from the mean result of these experiments one unit = 400 metre-kilogrammes.

307. **Other Physical Processes.**—Wherever heat is produced by any process, this process can perform work ; but the work performed causes loss of heat, or the heat produced by any process is diminished when at the same time work is performed.

Let a current pass through a magnetising spiral in an electro-magnetic rotatory arrangement. Then the wire becomes heated and the heat produced = $\kappa (i)^2 \times \text{resistance} (= R)$, i being the intensity, and κ some constant factor. But the heat is proportional to the consumption of zinc.

If now the resistance is doubled, then the intensity is half, and also the consumption of zinc is half, of what it was at first. But now we should have,

$$\text{Heat}_2 = \kappa \left(\frac{i}{2}\right)^2 2R = \frac{1}{2} \kappa i^2 R = \frac{1}{2} \text{ heat}_1.$$

The heat is half, the intensity is half, the consumption of zinc is half.

But as the electro-magnet begins to rotate, the intensity decreases with the increase of velocity of rotation.

Suppose that everything is so arranged that the intensity of current in the case of the rotating motor is half that of the same when at rest. Then the consumption of zinc is half. But the heat produced is now quite different. For the intensity is half, but the resistance is still the same :

$$\therefore \text{Heat}_3 = \kappa \left(\frac{i}{2}\right)^2 R = \frac{1}{4} \kappa i^2 R = \frac{1}{4} H_1,$$

or half the consumption produces only $\frac{1}{2}$ H, because the other $\frac{1}{2}$ H has done a corresponding equivalent of work.

308. **Melting of Ice.**—Let 1 k. of ice at 0° be in a vessel, under one atmospheric pressure. As long as the pressure is constant, if heat is conveyed to the ice, it becomes water. Heat required $= r = 79.035$ units. The analogy between fusion and vaporisation permits to apply also in this case the second law of thermodynamics.

$$\text{Now } u = \frac{r}{AT}, \therefore \phi = \frac{r}{ATu}$$

But ϕ is unknown in this case.

The volume of 1 kilogramme of *water* of temperature $0^{\circ} = 0.001$ cubic metre; of ice $= 0.00109 = w$.

$$\therefore u = v - w = -0.00009$$

$$\therefore \phi = \frac{-79.035 \times 424}{273 \times 0.00009}$$

ϕ = difference of pressure corresponding to a lowering of temperature of 1° . If in atmospheres

$$\phi = \frac{-79.035 \times 424}{273 \times 0.00009 \times 10333} = 132$$

\therefore an increase of pressure of 132 atmospheres lowers the freezing-point 1° ; of 1 atmosphere lowers it by 0.0075° c.

BOOK THE THIRD.

VARIOUS PRACTICAL APPLICATIONS OF THE EFFECTS OF HEAT.



CHAPTER XV.

COMBUSTION.

309. **Heat developed in chemical combination.**—It has been already explained that when two substances enter into chemical combination, so as to form a new compound, heat is generally either developed or absorbed ; so that, although the components before their union have the same temperature, the temperature of the compound which results will be generally above or below this common temperature, and sometimes considerably so.

If no change in the state of aggregation of the constituents is produced by their union, this phenomenon is explained by the specific heat of the compound being less or greater than that of the components, according as the temperature of the compound is greater or less. If greater, it is because, the specific heat being less, the actual quantity of heat contained in the compound gives it a higher temperature ; if less, because it gives it a lower temperature.

If the state of aggregation of either or both of the components be changed, heat which was latent becomes sensible, and raises the temperature of the compound ; or heat which was sensible becomes latent, and lowers it. Thus, when a solid mixed with a liquid is dissolved in it, the solid in liquefying absorbs and renders latent the same quantity of heat which would have been necessary to melt it. This heat, being abstracted from the sensible heat of the compound, lowers the temperature. This phenomenon has been already noticed in the case of freezing mixtures.

310. **Combustion.**—But of all the cases in which heat is developed by chemical combination, the most important are those in which combustion is produced. When the quantity of heat suddenly developed by the chemical combination of two bodies renders the compound luminous, the bodies are said to burn, and the phenomenon is called *combustion*. To the phenomenon of combustion popular names have been given, such as : *fire* ; or, *flame*.

Flame is gas rendered *white hot* by the excessive heat developed in the combination which produces it.

It happens that, among the infinite variety of substances whose combination is productive of this class of phenomena, one of the two combining bodies is almost invariably oxygen gas. A few other substances, such as chlorine, bromine, and iodine, produce similar effects ; but in all ordinary cases of combustion, and universally where that effect is resorted to as a source of artificial heat, one of the combining substances is oxygen gas.

On this account this gas has been called a *supporter of combustion*.

The substances which, combining with it, produce the phenomenon of combustion, are called *combustibles*.

The class of combustible substances which are commonly used for the production of artificial heat is called *fuel*. Such, for example, are pit coal, charcoal, and wood.

Another class of combustibles is used for the production of artificial light : such, for example, are oil, wax, and the gas extracted from certain sorts of pit coal, from oil, wax, and from certain sorts of wood, such as the pitch pine.

The principal constituents of all these combustibles, whether used for the production of heat or light, are those denominated by chemists *carbon* and *hydrogen*.

311. **Carbon.**—This is the name given to charcoal when it is absolutely pure, which it never is as it is obtained by the ordinary industrial processes. It is in that state combined with various heterogeneous and incombustible substances. In the laboratories of chemists it is separated from these, and obtained in a state of perfect purity, being there distinguished from the charcoal of commerce by the name *carbon*.

Carbon, having never been resolved by any chemical agent into other constituents, is classed in chemistry as a simple and elementary body, which enters largely into the composition of a numerous class of bodies which are found in nature, or produced in the processes of industry, the sciences, and the arts.

A quantity of charcoal being placed in a furnace through

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which a draught of air is maintained, if a part of it be heated to redness, the entire mass will soon become incandescent, and will emit a reddish light, which will be whiter as the air is passed through it more briskly, and will emit considerable heat. The charcoal will gradually decrease in quantity, and at length will disappear altogether from the furnace, under which a small portion of ashes consisting of incombustible matter will remain. If the charcoal had been pure—that is, if it had been carbon—it would have altogether disappeared, no ash whatever remaining.

This phenomenon is an example of combustion. The heat and light developed during the process here described are commonly called fire.

To comprehend what takes place in this process, we must consider that, as the air passes through the charcoal, the oxygen gas, which forms one-fifth part of it, enters into combination with the pure carbon. A compound is thus formed consisting of carbon and oxygen. The formation of this compound is attended with so great a production of heat that not only the compound itself, but the charcoal, from which it is evolved, is raised to a very elevated temperature.

The compound thus produced is a gas called carbonic acid.

The air which enters the furnace being a mixture of nitrogen and oxygen, that which rises from it after the combustion has been produced is a mixture of nitrogen and carbonic acid; the nitrogen having passed through the furnace without suffering other change than an increase of temperature, while the oxygen has been converted into highly-heated carbonic acid.

Several questions, however, arise out of this explanation. How is it known that such combination really takes place between the carbon and oxygen? If it do, in what proportion do they combine? How does it appear that the nitrogen, which forms four-fifths of the air which passes through the furnace issues unaltered?

To supply satisfactory answers to these questions, it is only necessary to bring the two constituents of common air separately into the presence of carbon under the conditions necessary to favour combination, and to ascertain their weights before and after the development of the phenomena.

Let a glass flask, containing thirty-two grains of oxygen gas, be inverted over mercury, as represented in *fig. 112*, and let a piece of carbon weighing a little more than twelve grains, supported in a platinum spoon, be introduced into it by means of a piece of bent platinum wire; let the sun's rays, concentrated by means of a burning-glass, be then directed upon the carbon through

the glass flask. The carbon will be ignited by the solar heat, and will burn in the oxygen with great splendour. When the combustion has ceased and the gas contained in the flask has cooled, it will be found that the mercury in the neck of the flask will stand at exactly the same elevation as it did before the combustion. The gas contained in the flask has, therefore, the same volume as before; nevertheless it is easy to show that it is by no means the same gas.



Fig. 112.

In the first place, if it be weighed, it will be found to weigh 44 instead of 32 grains; and if the unburned residue of the carbon be weighed, its weight will be found to be 12 grains less than it was before the experiment. The inference is, that 12 grains of the carbon have combined with the 32 grains of the oxygen previously contained in the flask, but that in thus combining, the carbon has not made any change in the volume of the gas.

If the gas contained in the flask be examined by the usual tests, it will immediately appear that it is no longer oxygen. No combustible will burn in it, and it will not support life by respiration. In fine, it will be found to be identical with the noxious gas called choke-damp, and to possess all the chemical characters of the gas called *carbonic acid*.

If the same flask, similarly filled with nitrogen gas be submitted to a like experiment, the result will not be the same. The solar rays concentrated on the charcoal will still render it red hot, but it will not burn nor undergo any other change. On removing the focus of solar rays from it, it will become gradually cool, and when removed from the flask will have the same weight as when introduced into it. The nitrogen which fills the flask will also be found to be unaltered.

It follows, therefore, that the *fire* produced when carbon burns in common air is nothing more than the heat and light developed in the formation of carbonic acid, by the combination of the carbon with the oxygen of the surrounding air, and that these substances combine in the proportion of twelve parts by weight of carbon to 32 of oxygen.

312. **Hydrogen.**—Like carbon, this is classed as a simple elementary substance; and also, like carbon, enters largely into the composition of a numerous class of bodies. Hydrogen com-

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biner with oxygen in the proportion of one part by weight of the former to eight of the latter to form water, and if the combination be formed in a pure or nearly pure atmosphere of the gases it is instantaneous, and accompanied by an explosion. If, however, the combination take place, as it may, in common air, the phenomena will be very different.

If pure hydrogen, compressed in a bladder or other reservoir, be allowed to issue from a small aperture, a light applied to it will cause it to be inflamed. It burns tranquilly without explosion, producing a pale yellowish flame and very feeble light, but intense heat. This is the effect attending the gradual and continual combination of the hydrogen, as it escapes from the aperture, with the oxygen of the surrounding air. It may be asked why the hydrogen issuing from the aperture does not combine with the oxygen of the air without the application of a flame to it? And also why, being once inflamed by the application of such a body, its continued application becomes unnecessary?

These questions are easily answered. The hydrogen gas has an affinity or attraction for oxygen, which is not strong enough to cause their combination at common temperatures; but when the temperature of the hydrogen is greatly elevated, its attraction for the oxygen becomes so exalted, that it enters into instant and spontaneous combination with it. Now, by applying the flame of a lamp or candle, or any other burning body, to the jet of hydrogen, its temperature becomes so greatly raised, and its attraction for oxygen consequently so exalted, that it enters directly into combination with the oxygen of the air which is in immediate contact with it at the moment.

But it is also asked how the continuance of the combination and the consequent maintenance of the flame takes place—the candle or lamp which produced its commencement being withdrawn? This is explained by the great quantity of heat produced by the combination of the hydrogen with the oxygen. The commencement of the combination being produced by the candle or lamp, the hydrogen and oxygen themselves, in the act of combining, develop an intense heat, and the succeeding portion of hydrogen gas, being in contact with them, becomes heated, and combines, like the former, with a fresh portion of oxygen. In the same manner, the heat developed by these being shared by the succeeding portion of gas, a further combination and development of heat takes place, and so on.

Thus, the combustion being once commenced, the heat necessary for its maintenance and continuance is developed in the

process itself, which accordingly goes on without the necessity of the substance being again kindled by the application of any flame.

The continuance of the combustion of carbon, whether in pure oxygen gas or in common air, is explained in the same manner.

313. **Flame.**—The combustion of carbon differs from that of hydrogen in this, that the former takes place without the production of *flame*. The charcoal being heated to redness, and still in the solid form, enters directly into combination with the oxygen of the surrounding air, and the carbonic acid which is formed, being a gas which is not luminous nor visible, simply disappears with the carbon. But in the case of hydrogen, the heat produced by the combustion is so intense as to render the gas itself luminous, just as intense heat will render a mass of iron red hot or white hot. When gas becomes thus luminous, it is called *flame*.

Flame, therefore, must be understood to be nothing more than matter in the aeriform, gaseous, or vaporous state, rendered so intensely hot as to become incandescent, and to emit light, just as would a bar of iron taken from a furnace.

It is easy to show that the product of the combustion of hydrogen is the vapour of water, which, by exposure to cold, can be reduced to the liquid state.

If a glass jar be held over a jet of inflamed hydrogen, as represented in *fig. 113*, the aqueous vapour formed by the com-

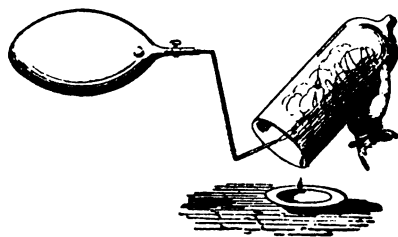


Fig. 113.

bination of the hydrogen with the oxygen of the surrounding air will be condensed upon the inside of the jar, and will appear first as a cloudy dew upon it, and, as the process is continued, it will increase in quantity, and, trickling down the

side of the jar, may be received in drops by a dish placed beneath it.

As we have stated above, the principal constituents of every species of combustible, whether used for heating or lighting, are carbon and hydrogen, and the products of their combustion are therefore generally carbonic acid and water, the latter being evolved in the form of vapour.

It happens, however, rarely that the hydrogen is evolved in the uncombined state. It is more generally combined with certain proportions of carbon, forming compound gases called in general *hydro-carbons*. These gases burn with a much whiter and more luminous flame than that of pure hydrogen, and they are therefore much better fitted for the purpose of illumination.

That the flame owes its whiteness and illuminating power to the carbon with which the gas is charged is proved by the fact that the more carbon the gas is charged with the whiter and brighter is the flame.

Of the more important hydro-carbons to be studied in relation to flame, there are two kinds, one of which contains twice as much carbon as the other: the one with less carbon is called light carburetted hydrogen or marsh-gas, and the other heavy carburetted hydrogen, or olefiant gas.

In light carburetted hydrogen 12 parts, by weight, of carbon are combined with 4 of hydrogen, and heavy carburetted hydrogen contains twice that proportion of carbon.

Light carburetted hydrogen is a little more than half the weight of its own bulk of common air. When pure, it has no odour; and it burns with a yellowish flame much more luminous than that of pure hydrogen. Like pure hydrogen, it forms a highly explosive mixture when combined in a certain proportion with common air, or, more properly, with the oxygen of common air, since the nitrogen has no influence on the phenomenon.

It is this gas which, under the name of *fire-damp*, produces occasionally such disastrous explosions in coal mines. Being contained in large quantities in the fissures and interstices of the seams of coal, it issues from them in the workings of the mines, and, being one-half lighter than common air, it first collects at the top of the working. After a certain time, by diffusion, a common property of all gases, it mixes with the air, and attains occasionally that proportion which renders it explosive. If a light be brought into it in this state an explosion takes place, producing those destructive consequences to the opera-

tives who happen at the moment to be present, with the details of which everybody has been so often rendered familiar.

This gas is also that which, over marshy ground and in stagnant pools, is produced by the decomposition of vegetable and animal matter. It is easy to verify this by actually collecting the gas from any stagnant pool. For this purpose, take a common funnel used for decanting liquors, and a bottle or beer-glass; immerse the latter in the water, and when it is filled, invert it under the water and raise it above the surface, keeping the mouth under the water. Then bring the inverted funnel under its mouth, the neck entering the bottle or glass; agitate the funnel, and the gas will rise from the water in bubbles, and will collect in the upper part of the bottle or glass.



Fig. 114.

The manner of performing this experiment is shown in *fig. 114*.

When the gas is thus collected, its inflammable nature may be ascertained by applying a light to it as it issues from the bottle.

Heavy carburetted hydrogen burns with a much whiter and more luminous flame. Its weight is very nearly equal to that of common air, and, therefore, nearly double that of the light carburetted hydrogen; hence it has acquired the epithet 'heavy.'

The products of the combustion of both kinds of carburetted hydrogen are carbonic acid and water, the former proceeding from the combination of the carbon, and the latter from that of the hydrogen with the oxygen of the air.

These points being understood, it will be easy to render intelligible the effects which are developed in all ordinary cases in which *fire* or *combustion* takes place.

The species of combustible used as fuel with which we are most familiar in this country is *pit coal*.

This substance, exclusive of some extraneous and combustible mineral ingredients which it contains in very small proportions, consists essentially of carbon, hydrogen, oxygen, and nitrogen.

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The proportion of carbon varies in different sorts of coal from 80 to 90 per cent., the hydrogen varying from 3 to 6 per cent., and the remainder consisting of oxygen and nitrogen.

In the heavy coal of Wales, called anthracite, the proportion of carbon is above 90 per cent., while that of the hydrogen is only 3 or 4 per cent. In the bituminous coal of Northumberland the proportion of carbon is about 87 per cent., and that of hydrogen from 5 to 6 per cent.

When a fire composed of such fuel is properly kindled and supplied with a draught of air necessary to sustain the combustion, the carbon will continue to combine with its proper proportion of oxygen, producing the corresponding quantity of heated carbonic acid, and rendering the solid part of the fuel red and luminous; and the hydrogen will at the same time combine with the respective proportion of oxygen, producing watery vapour, and rendering the gases as they issue from the fuel luminous, or, what is the same, converting them into flame.

The flame will be faintly luminous and bluish if any part of the gases be pure hydrogen; it will be yellowish and a little more luminous if they be light carburetted hydrogen; and it will be very white and very luminous if they be heavy carburetted hydrogen.

Thus all the phenomena exhibited by a common coal fire—the red unflaming fuel—the faint blue flames occasionally seen—and, in fine, the white brilliant flame which most commonly issues from the fissures of the coal, are severally explained and accounted for.

314. **Products of Combustion.**—It has been shown that in combustion 12 parts, by weight, of carbon combine with 32 of oxygen, or, what is the same, 1 part with 2 $\frac{2}{3}$. It has also been shown that, in the combustion of hydrogen, 2 parts by weight of that gas combine with 16 of oxygen. Now, by these simple numerical data may be easily explained the effects of a common coal fire upon the air which feeds and sustains it.

It is thus found that in burning 10 lb. of coal the oxygen contained in 1551 cubic feet of air is altogether absorbed.

To keep the atmosphere of a room in which a fire of such coal is burned fresh and pure, it would be, therefore, necessary to supply fresh air at the rate of 155 cubic feet for every pound of coal which is burned.¹

¹ In the preceding explanation we have omitted to take into account the effect of a small proportion of oxygen which enters into the composition of coal. This, however, is not important for our consideration, and it would be needless to complicate the calculation by introducing it.

Wood is a combustible generally used for the production of artificial heat in countries where coal is not so cheap and abundant as in England. This fuel, like coal, consists principally of carbon and hydrogen in various proportions, according to the sort of wood. All kinds of wood contain also a proportion of oxygen, as a constituent, much greater than is found in coal.

The following small table will best show the relative percentage composition of wood and other kinds of fuel :—

	Carbon	Hydrogen	Nitrogen and Oxygen
	per cent.	per cent.	per cent.
Woody fibre	52·65	5·25	42·10
Peat from the Shannon	60·02	5·88	34·10
Lignite from Cologne	66·96	5·25	27·79
Earthy coal from Dax	74·20	5·89	19·91
Wigan Cannel	85·81	5·85	8·34
Newcastle Hartley	88·42	5·61	5·97
Welsh anthracite	94·05	3·38	2·57

Wood, when green, contains a considerable proportion of water. In the combustion of such wood a large proportion of the heat developed is absorbed in the evaporation of this water, and is, therefore, lost for heating purposes. Wood used as fuel should, therefore, be kept until this water, or the chief part of it, has been evaporated. For the same reason, wood kept for fuel should be as little exposed to moisture or damp as possible.

All fatty, oily, and waxy substances are combustible, whether in the liquid or solid state. They consist of the same constituents as coal and wood, but combined somewhat differently and in different proportions. Most substances of this class, burning with a flame of more or less brilliancy, are used for the purposes of artificial illumination.

Whale, sperm, olive, and cocoa-nut oils, wax, spermaceti, and tallow are examples of this class of combustibles.

Whatever be the sort of combustible, or whatever be the purpose to which it is applied, whether for heating or lighting, it will be evident from the explanations which have been here given, that the combustion cannot be maintained with the necessary activity, unless expedients be provided for the supply

of the quantity of oxygen which must enter into combination with it.

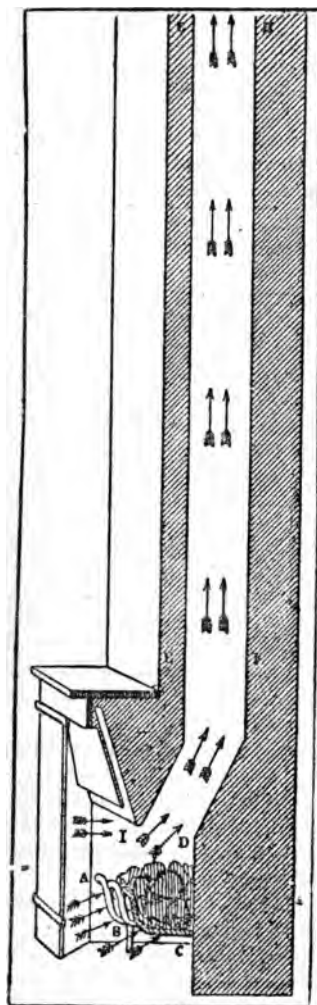


Fig. 115.

is measured by the difference between its weight and that of

315. **Construction of Grates.**—The construction of grates, stoves, and chimneys is, therefore, designed to attain this end by causing such a volume of common air to pass through the fuel as is necessary and sufficient to combine with it. The more air which thus passes through the fuel, the more rapid and abundant will be the combination, and the more active and vivid the combustion.

The current of air which passes through a common grate is produced by the draught of the chimney. The column of air included in the chimney, being raised to a higher temperature than that of the external air, is rarefied and lighter, bulk for bulk, than the external air, and has, therefore, a tendency to ascend like that which oil would have in water. As it ascends the air from the room must rush in to fill its place. A part of this air will pass through the bottom and front of the grate, and a part will enter at the opening of the fire-place over the grate. This will be more easily understood from *fig. 115*. The front of the grate is A B, and the bottom B C, having the ash-pit below it. The opening over the grate is A I, and E F G H is the flue of the chimney. The ascensional force of the column of air in the flue

an equal volume of the external air. The air which replaces that which ascends in the flue enters the bottom B C, the front B A of the grate and the opening A I above it, as indicated by the arrows. The former portions, passing through the burning fuel, supply to it the oxygen gas necessary to combine with it, and thus maintain the combustion. These portions, after passing through the interstices of the fuel, and after the oxygen, or a part of it, has combined with the fuel, issue from the top of the fuel, being then a mixture of nitrogen, such portion of oxygen as may not have combined with the fuel, carbonic acid and aqueous vapour, the two last being the products of the combination of the oxygen with the carbon and the hydrogen of the fuel.

All these gases issuing from the burning fuel at a high temperature, and mixing with the cold air which enters the chimney through the opening A I, render the column of air in the flue so warm as to give it the buoyancy necessary to sustain the draught.

When the fire is first kindled in the grate, if the air in the chimney have the same temperature as the external air, it will have no buoyancy, and there will be no draught. In this case the chimney will generally be found to smoke. This inconvenience may be sometimes removed by opening the windows, so as to fill the room with air as cold as the external air, and therefore colder than the air in the chimney. If, however, this be found insufficient, the air in the flue may be warmed and the necessary draught produced by holding under the chimney any blazing combustible.

The draught through the grate may be greatly increased in intensity by stopping up, either partially or completely, the opening A I. By this expedient all the air necessary to replace that which ascends in the chimney must pass through the fuel in the grate. If the magnitude of the opening be, for example, three times the magnitude of the front and bottom of the grate, four times as much air will thus pass through the fuel as would pass through it when the opening A I is not closed, supposing the draught in the chimney to be the same in both cases.

But, in fact, the draught in the chimney will be greatly augmented by this process; for, so long as the opening A I is not closed, the air which fills the chimney will consist of a mixture of that which passes through the burning fuel, which is raised to a high temperature, and the much larger portion which passes into the chimney through the opening A I, and which, being cold, lowers the temperature, and therefore diminishes the buoyancy

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of the air in the chimney. But when all the air which passes through A 1, by closing that opening, is made to pass through the burning fuel, it is raised to a high temperature, which, not being lowered by admixture with any air not passing through the fuel, fills the chimney with air raised to a very elevated temperature, and which therefore produces in the chimney a much stronger upward current.

Thus the effect of closing the opening A 1 is to stimulate the fire, not only by causing to pass through it all the air which previously entered the opening A 1, but also by augmenting the draught in the chimney.

From what has been explained above, it will be perceived that an open fire-place, such as is represented in *fig. 115*, serves the double purpose of warming and ventilating.

All the air which enters the chimney, whether it passes through the grate or through the opening above the grate, must be replaced by an equal volume of fresh air from without, which must find its way through the interstices of doors and windows, or through other openings provided expressly for its admission. That part of the air which passes through the grate subserves the double purpose of warming and ventilation. It warms by stimulating and maintaining the combustion of the fuel, and it ventilates by leaving in the room a void into which an equal volume of fresh air must enter. That portion of air which enters the chimney through the opening above the grate has no effect, direct or indirect, in warming, but its effect in ventilating is just so much greater than that of the air which passes through the grate, as the magnitude of the opening above the grate is greater than the magnitude of the spaces between the bars in the front and bottom of the grate.

The necessity for ventilation is so much the greater as the room is smaller and lower, and as the causes of the pollution of its air are more numerous and active. The air of a room is deprived of its oxygen, and rendered unfit for respiration by several causes. Each person who is present in the room absorbs oxygen by respiration. It is calculated that an adult of average size absorbs about a cubic foot of oxygen per hour by respiration, and consequently renders five cubic feet of air unfit for breathing. It is also computed that two wax or sperm candles absorb as much oxygen as an adult. It follows, therefore, that to keep the air of a room pure, five cubic feet for every person, and two and a half cubic feet for every candle in the room should pass per hour into the chimney, or through some other opening, and an equal volume of fresh air should be admitted.

Plants give out oxygen by day, but absorb it by night. Their presence in a room by day is, therefore, innocuous, but at night they have the effect of polluting the air, and should never be admitted except where there are ample means of ventilation.

A crowded room, illuminated with many candles and lamps, and, as generally happens, without a fire, soon becomes filled with air in which there is a deficient proportion of oxygen, and a corresponding volume of carbonic acid, unless means be provided, which is rarely the case, for other ventilation besides that of the chimney. Hence it arises that persons of delicate habits, especially those whose lungs are defective, in such a room, soon become sensible of general uneasiness, and are often affected with headache.

The manner in which the flame of lamps and candles is produced and maintained will require some explanation.

When a candle is lighted, the heat developed at the extremity of the wick melts the wax or tallow immediately below it, and, thus liquefied, it is drawn up through the interstices of the wick by what is called capillary attraction. When it comes in contact with the flame, it boils, and is converted into vapour, which rises over the wick. This vapour having a very high temperature, and exercising a strong attraction for the oxygen of the surrounding

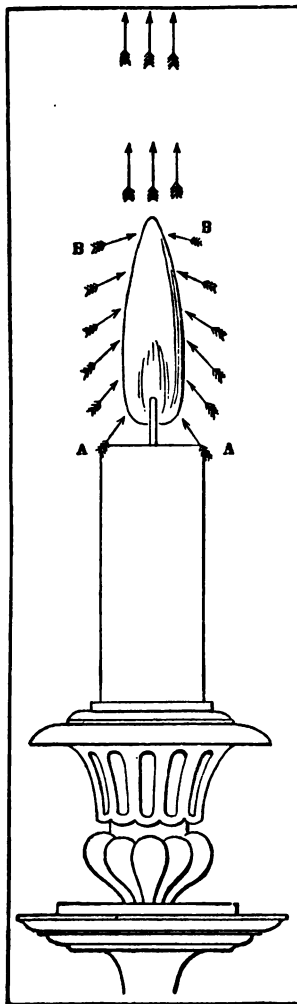


Fig. 116.

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air, enters into combination with it, and, becoming luminous, forms the flame around and above the wick. Within the flame arises a constant current of the vapour of the combustible, and outside it currents of air carry to the surface of the flame the oxygen which produces the combustion and the light. The combustible vapour and the oxygen meeting at the surface of the flame, there enter into combination, and the vapour burns. Within the flame no combustion takes place, and no light is produced.

In *fig. 116* the wick and flame are represented. Within the flame currents of combustible vapour proceed from the wick to all parts of the surface of the flame. The arrows at the sides of the flame outside its surface represent the currents of the surrounding air produced by the heat of the flame. The oxygen, being attracted by the intensely heated combustible vapour, approaches it, and, by combining with it, sustains the combustion and produces the light. The arrows above the flame indicate the current of heated air, carbonic acid and aqueous vapour, the products of the combustion, which form an ascending column above the flame.

It will be apparent from what has been here stated, that the luminous part of the flame is merely superficial. The vapour within the surface of the flame not having yet come into contact with the oxygen, and therefore not having entered into combustion, cannot be luminous. The flame, therefore, so far as relates to light, is hollow, or rather it is a column of combustible vapour, the surface being the only part which burns, and therefore the only part which is luminous. As this vapour ascends from the interior of the flame it comes successively into contact with the oxygen of the air, is burnt, and becomes luminous, the column of light gradually contracting in diameter until it is reduced to a point. The flame thus tapers to a point until all the vapour produced by the boiling matter on the wick receives its due complement of oxygen, and passes off. It speedily loses that high temperature which renders it luminous, and the flame terminates.

In lamps of various construction, expedients are adopted to increase the magnitude of the luminous surface of the flame, and the intensity of the combustion. This is effected by modifying the form and magnitude of the wick, by feeding it with an abundant supply of oil, and by maintaining strong and steady currents of air at all parts of its surface to sustain the combustion.

The most common form of wick used for lamps of strong illuminating power, is that of a hollow cylinder, varying from

an inch to three inches in circumference. This wick, being attached at its base to a small thin ring of metal, is let down into the reservoir of oil, through a space included between two concentric tubes, one of which has a less diameter than the other, the space between them being a little wider than the thickness of the wick. The wick is usually from two and a half to three inches long, and descends through this space between the tubes to a certain depth. This space communicates with the reservoir of oil from which the oil is forced up either by the action of a pump worked by a main-spring, through the intervention of wheelwork, as in the Carcel lamp, or by the more direct action of a strong spiral spring, as in the Moderator lamp, or by the pressure of oil contained in a reservoir above the level of the wick, as in the old English ring-lamp, called the Sinumbral lamp, and a variety of other forms constructed on the like principle. A more detailed description of the hydrostatical principles involved in lamp-construction is given in the treatise on *HYDROSTATICS* in this series, page 284 to 291.

The flame issuing from such a wick is obviously a hollow cylinder, and requires to be fed with air, both at its exterior and interior surfaces. A current of air in contact with the interior surface of the flame is maintained by carrying the lesser of the two tubes, between which the wick is included, down through

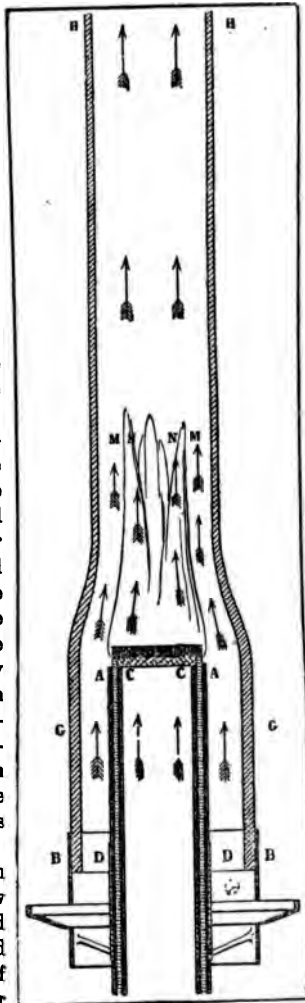


Fig. 117.

internal tube c c, passing in contact with the internal surface of the flame as indicated by the arrows. The cylindrical flame, ascending from the wick is represented at A M C N, and the course of the ascending column in the chimney is represented by arrows.

316. Temperature necessary for combustion.—The temperature necessary to produce combustion is different for different substances; phosphorus combines with oxygen, and burns in the atmosphere, if raised to about 60°C . Hydrogen gas will not burn till raised to incandescence. According to Sir H. Davy, the temperatures necessary for the combustion of the several combustibles here named are in the following order:—

- | | |
|----------------------------|---------------------------|
| 1. Phosphorus. | 7. Sulphuretted hydrogen. |
| 2. Phosphoretted hydrogen. | 8. Alcohol. |
| 3. Hydrogen and chlorine. | 9. Wax. |
| 4. Sulphur. | 10. Carbonic oxide. |
| 5. Hydrogen and oxygen. | 11. Carburetted hydrogen. |
| 6. Olefiant gas. | |

If a jet of hydrogen gas be directed upon a small mass of spongy platinum, the metal will become incandescent, and will continue so as long as the gas acts upon it, without, however, suffering any permanent change. The jet of hydrogen is ignited by the red-hot spongy metal.

An apparatus for producing an instantaneous light has been contrived on this principle. By turning a stop-cock communicating with a small bottle in which the gas is generated in the usual way, the jet of gas is thrown upon a small cup containing the spongy metal, which, immediately becoming incandescent, ignites the jet of hydrogen directed upon it, which thus is capable of lighting a match.

Some other metals—palladium, iridium, and rhodium—appear to be susceptible of the same effect.

This effect is explained by the power of many substances in a state of minute division of absorbing and condensing a great quantity of gaseous matter within their pores. In this case the spongy platinum is supposed to condense a vast amount of oxygen from the air, and if hydrogen be presented to the condensed gas, the two gases will be placed in such intimate contact that their chemical affinity will act, and they will combine to form water. The heat thus liberated is sufficient to make the platinum tinder red hot, and so to inflame the hydrogen which subsequently issues from the jet.

317. Quantity of heat developed by combustibles.—The determination of the quantity of heat evolved by different com-

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bustibles is a question not only of great scientific interest, but of considerable importance in the arts and manufactures. The mutual relation between the quantities of the combustible, the oxygen, and the heat developed, if accurately ascertained, could not fail to throw light, not only on the theory of combustion, but on the physics of heat in general. In the arts and manufactures, the due selection of combustible matter depends in a great degree upon the quantity of heat developed by a given weight in the process of combustion.

Nevertheless, there is no part of experimental physics in which the process of investigation is attended with greater difficulties. Experiments were made on certain combustibles by Lavoisier and Laplace, by burning them in their calorimeter, and observing the quantity of ice dissolved by the heat which they evolved. Drs. Dalton and Crawford, Count Rumford and Despretz, as well as Sir H. Davy, made various experiments with a like object. It was not, however, until the subject was taken up by Dulong that any considerable progress in discovery was made. Unhappily, that eminent experimental inquirer died before his researches were completed. Much valuable information has been collected from his unfinished memoranda. The inquiry has since been resumed by MM. Favre and Silbermann, and has been prosecuted with much zeal and success by many physicists. The estimates which the two last-mentioned observers have obtained of the quantities of heat developed in the combustion of various substances are found to be in general accordance with those which appear to have been obtained by Dulong, in the case where they have operated on the same combustible. Thus, in the case of hydrogen, the most important of the substances under inquiry, Dulong found the heat developed to be expressed by 34601; while MM. Favre and Silbermann estimated it at 34462, with relation to the same thermal unit.

In the following table is given the heat developed in the combustion of the substances named in the first column; the thermal unit being the heat necessary to raise a weight of water equal to that of the combustible, one degree of the scale of Fahrenheit's thermometer:—

Names of Substances	Formulæ	Quantity of Heat given by 1° of Combustion
Hydrogen, at 59°	—	62031·6
Carbon from C to CO ²	—	14544·7
Carbon, from sugar, from C to CO ²	—	14471·6
Carbon, from gas retorts	—	14485·1
Graphite, natural, No. 1	—	14060·7
Graphite, from high mines, No. 1	—	14013·5
Graphite, natural, No. 2	—	14006·7
Diamond	—	13986·2
Graphite, from high mines, No. 2	—	13926·8
Diamond, heated	—	14181·7
Oxide, from carbon, at CO ²	—	4324·9
Gas, marsh	C ² H ⁴	23513·4
„ olefiant	C ⁴ H ⁴	21344·0
Paramyline	C ¹⁰ H ¹⁰	20683·8
Amylene	C ²⁰ H ²⁰	20346·3
„	C ³² H ³²	20278·8
Cetine	C ³² H ³²	19941·3
Metamyline	C ¹⁰ H ⁴⁰	19671·3
Ether, sulphuric	HO ² + C ⁸ H ⁸	16248·6
„ valeric	HO ² + C ²⁰ H ²⁰	18338·4
Spirit of wood	HO ² + C ² H ²	9542·7
Alcohol	HO ² + C ⁴ H ⁴	12931·2
„ valeric	HO ² + C ¹⁰ H ¹⁰	16125·5
„ ethalic	HO ² + C ³² H ³²	19132·6
Acetone	C ⁶ H ⁶ + O ²	13149·0
Aldhyde, ethalic	C ³² H ³² O ²	18616·0
„ stearic	C ³⁸ H ³⁸ O ²	18892·8
Formiate of methylene	C ⁴ H ⁴ O ⁴	7555·3
Acetate „ „	C ⁶ H ⁶ O ⁴	9615·6
Formiate of alcohol	C ⁶ H ⁶ O ⁴	9502·2
Ether, acetic	C ⁸ H ⁸ O ⁴	11326·9
Butyrate of methylene	C ³⁰ H ¹⁰ O ⁴	12237·3
Ether, butyric	C ¹² H ¹² O ⁴	12763·6
Valeriate of methylene	C ¹⁴ H ¹⁴ O ⁴	13276·1
„ „ alcohol	C ¹⁴ H ¹⁴ O ⁴	14102·8
Acetate of alcohol, valeric	C ²⁰ H ²⁰ O ⁴	14348·2
Ether, valeramic	C ²⁰ H ²⁰ O ⁴	15378·5
Acid, formic	O ⁴ + C ² H ²	3600·0
„ acetic	O ⁴ + C ⁴ H ⁴	6309·4
„ butyric	O ⁴ + C ⁸ H ⁸	10121·4
„ valeric	O ⁴ + C ¹⁰ H ¹⁰	11590·2
„ ethalic	O ⁴ + C ³² H ³²	16956·0
„ stearic	O ⁴ + C ³⁸ H ³⁸	17676·0
„ phrenic	C ¹² H ⁸ O ²	14116·1
Terebene	C ²⁰ H ¹⁶	19193·4
Essence of turpentine	C ²⁰ H ¹⁶	19533·6
„ „ citron	C ²⁰ H ¹⁶	19726·2

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Names of Substances	Formula	Quantity of Heat given by 1° of Combustion
Sulphur, native melted	$C^{20} H^{10}$	3998·0
Sulphur, at instant of crystallisation	—	4065·1
Sulphur of carbon	—	6120·9
Carbon burnt with peroxide of azote at 10°	—	20084·2
Decomposition of peroxide of azote	—	19962·9
Decomposition of water oxygenated, 1 grain oxygen	—	2345·4
Decomposition of oxide of silver absorbs	—	— 39·8
Iceland spar for CO^2 and C to O absorbs	—	— 554·6
Aragonite combined gives	—	+ 68·9
Aragonite separated absorbs	—	— 554·6
Aragonite separated after combination absorbs	—	— 485·6

CHAPTER XVI.

ANIMAL HEAT.

318. **Temperature of organised bodies.** — Organised bodies in general present a striking exception to the law of equalisation of temperature, since, with some rare exceptions, these bodies are never at the temperature of the medium which surrounds them. The human body, as is well known, has a permanent and invariable temperature much more elevated than that of the atmosphere. The animals of the polar regions are much warmer than the ice upon which they rest, and those which inhabit tropical climates colder in general than the air they respire. The temperature of the bodies of birds is not that of the atmosphere, nor of fishes that of the sea.

There is, therefore, in organised bodies, some proper source of heat, or rather some provision by which heat and cold can be produced at need ; for the ponderable matter which composes the bodies of these creatures must, like all ponderable matter, be subject to the general law of equilibrium of temperature. It is therefore necessary to ascertain what is the tem-

perature of organised creatures; what are the quantities of heat which they evolve in a given time to maintain this temperature; and what is the physical apparatus by which that heat is elaborated.

319. **Temperature of blood.**—The temperature of the blood in the human species is found to be the same throughout the whole extent of the body, and is that which is indicated by a thermometer, whose bulb is placed under the tongue and held there until the mercurial column becomes stationary. This temperature is 98°·6 on Fahrenheit's scale, subject to extremely small variations, depending on health, age, and climate.

Dr. John Davy, Inspector of Army Hospitals, availed himself of the opportunities presented by his professional appointment, and of a voyage made by him to the East, to make an extensive and valuable series of observations on the temperature of the blood in man, in different climates, at different ages, and among different races, as well as upon the inferior animals. These observations were made between 1816 and 1820.

The first series of observations were made during a voyage from England to Ceylon, and, therefore, under exposure to very various climates and temperatures. The temperature of the blood was observed by means of a sensitive thermometer applied under the tongue near its root, with every precaution necessary to ensure accuracy. The principal results obtained are collected and arranged in the following tables:—

TABLE I.

Showing the Temperatures of the Blood of 13 Individuals in different Climates.

Age	Air, 60°	Air, 78°	Air, 79°·5	Air, 80°
24	98·5	99	100	99·5
28	—	99·5	99·5	99·5
25	98·25	98·75	98·5	99·75
17	—	99	99	100
25	98	99	99	99·5
20	98·75	98	99·5	100
28	98·25	98·75	99	99·5
25	98	—	—	101
40	—	—	—	99·75
43	—	—	—	99
40	—	—	—	99·5
13	—	—	—	100
4	—	—	—	99·5

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TABLE II.

Showing the Temperatures of the Blood of 6 Individuals in different Climates.

Age	Air, 69°	Air, 83°	Air, 82°	Air, 84°
35	98	99	102	98·5
20	98	99	101	98
40	99	99	98·5	98
35	98	99·75	99	98
20	98	99·5	99	—
24	98	99·5	100	—

TABLE III.

Showing the Temperatures of the Blood in the same Individual at different Hours of the Day.

Hour	Air	Blood	Sensation
6 A.M.	60·5	98	Cool
9	66	97·5	Cold
1 P.M.	78	98·5	Cool
4	79	98·5	Warm
6	71	99	Warm
11	69	98	Cool

TABLE IV.

Showing the Limits between which the Temperature of the Blood in different Races was observed to vary in India. Air, 75° to 81°.

Races	Temperature
Cape Hottentots	96·5 to 99·5
Cingalese	100 „ 101·5
Albinos	101 „ 101·75
Half caste	100 „ 102
White children	101 „ 102
Kandians	97·5 „ 99
Vaidas	98 „ 98·5
African Negroes	98·5 „ 99·5
Malays	98·5 „ 99·5
Sepoys	98 „ 100
English	98 „ 101

TABLE V.

Showing the Temperature of the Blood observed in different Species of Animals.

Name	Air	Temperature	Place of Observation
<i>Mammalia.</i>			
Monkey	86	104½	Colombo
Pangolin.	80	90	—
Bat	82	100	—
Vampyre	70	100	—
Squirrel	81	102	—
Rat	80	102	—
Guinea-pig	—	102	Chatham
Hare	80	100	Colombo
Ichneumon	81	103	—
Jungle cat	80	99	—
Cur dog	—	103	Kandy
Jackal	84	101	Colombo
Cat	60	101	London
"	79	102	Kandy
Felix pardus	81	102	Colombo
Horse	80	99·5	Kandy
Sheep	—	101 to 104	Scotland
"	67	103 to 104	Cape
"	78	104 to 105	Colombo
Goat	78	103 to 104	Colombo
Ox	Sumr.	100	Edinburgh
"	80	102	Kandy
Elk	78	103	Mount Lavinia
Hog	75	105	Doombera
"	80	105	Mount Lavinia
Elephant	80	99·5	Colombo
Porpoise	72	100	Lat. N. 8° 23' at sea
<i>Birds.</i>			
Falcon	77·5	99	Colombo
Screech-owl	60	106	London
Jackdaw	85	107	Kandy
Thrush	60	109	London
Sparrow	80	108	Kandy
Pigeon	60	108	London
"	78	109·5	Mount Lavinia
Jungle fowl	78	107·5	Ceylon
"	83	108·5	—
Common fowl	40	108·5	Edinburgh
" "	78	110	Mount Lavinia
" "	—	108	—
Guinea fowl	—	110	—

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TABLE V.—*continued.*

Name	Air	Temperature	Place of Observation
<i>Birds.</i>			
Turkey	—	109	—
Procellaria equinoxialis	79	103·5 to 105·5	Lat. N. 2° 3'
P. capensis	59	105·5	Lat. S. 34° 1' at sea
Common hen	77	110	Mount Lavinia
„ cock	77	111	—
Chicken	77	111	—
Malay cock	—	110	—
Goose	—	106 to 107	—
Duck	—	110—111	Mount Lavinia
Teal	—	108—109½	—
Snipe	83	98	Colombo
Plover	—	105	Ceylon
Peacock	83	105—108	Kornegalle
<i>Amphibia.</i>			
Testudo midas	79·5	84	Lat. N. 2° 7'
„ „	80	88·5	—
„ „	86	85	Colombo
T. geometrica	61	62·5	Cape
„ „	80	87	Colombo
Rana ventricosa	80	77	Kandy
Common frog	60	64	Edinburgh
Iguana	82	82½	Colombo
Serpents	81½	88½	—
„ „	82½	84½	—
<i>Fishes.</i>			
Shark	71½	77	Lat. S. 8° 23'
Bonito	78½	82*	Lat. S. 1° 14'
Trout	56	58	Edinburgh
„ „	56	58	L. Katrine
Eel	51	51	Chatham
Flying-fish	77	78	Lat. N. 6° 57'
<i>Mollusca.</i>			
Oyster	82	82	Mount Lavinia
Snail	76½	76 to 76½	Kandy
<i>Crustacea.</i>			
Crayfish	80	79	Colombo
Crab	72	72	Kandy

* This was the temperature of the heart, which lies near the surface. In the deeply-seated muscles the temperature was 99.

TABLE V.—*continued.*

Name	Air	Temperature	Place of Observation
<i>Insects.</i>			
Scarabæus pilularius .	76	77	Kandy
Glowworm . . .	73	74	—
Blatta orientalis . .	83	74—75	—
Gryllus hæmatopus? .	62	72½	Cape
Apis ichneumonia? .	75	75	Kandy
Papilio agamemnon .	78	80	—
Scorpio afer . . .	79	77½	—
Julus	80	78½	--

320. **Results of these observations.**—The conclusions deduced from these observations and experiments are, that the temperature of man, although nearly constant, is not exactly so; that it is slightly augmented with the increased temperature of the climate to which the individual is exposed; that the temperature of the inhabitants of a warm climate is higher than those of a mild; and that the temperature of the different races of mankind is, *cæteris paribus*, nearly the same. This is the more remarkable, inasmuch as, among those whose temperatures thus agree, there is scarcely any condition in common except the air they breathe. Some, such as the Vaida, live almost exclusively on animal food; others, as the priests of Buddh, exclusively on vegetables; and others, as Europeans and Africans, on both.

Of all animals birds have the highest temperature; mammalia come next; then amphibia, fishes, and certain insects. Mollusca, crustacea, and worms stand lowest in the scale of temperature.

Experiments were made by MM. Breschet and Becquerel to ascertain the variation of the temperature of the human body in a state of health and sickness. They employed for this purpose compound thermoscopic needles, composed of two different metals, which, being exposed to a change of temperature, indicated with great sensitiveness the sensible heat by which they were affected, by means of a galvanometer on a principle similar to the electroscopic apparatus used by M. Melloni, already described (art. 275). The needles were adapted for use by the method of acupuncture.

It was found that in a state of fever the general temperature of the body sometimes rose from 1°·8 to 3°·6.

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It was also ascertained, in several cases of local chronic and accidental inflammation, that the temperature of the inflamed part was a little higher than the general temperature of the body, the excess, however, never amounting to more than from $1^{\circ}8$ to $3^{\circ}6$.

It resulted from these researches that, in the dog, the arterial blood exceeds in temperature the venous by about $1^{\circ}8$. It was also found that the temperature of the bodies of the inhabitants of the valley of the Rhone and those of the Great St. Bernard, both men and inferior animals, were the same.

A series of experiments was made by Lavoisier and Laplace to determine, by means of their calorimeter, already described, the quantity of heat developed in a given time by various animals; but more recently much more extensive researches in this department were made by Dulong, which have produced important results. In these experiments the animal under examination was shut up in a copper cage sufficiently capacious to be left at ease, and being submerged in a glass vessel of water, the air necessary for respiration was supplied and measured by a gasometer, while the products of respiration were carried away through the water, to which they imparted their heat, and were afterwards collected and analysed. Each experiment was continued for two hours. After the proper corrections had been applied, the heat developed by the animal was calculated by the heat imparted to the water.

Dulong determined these thermal quantities with great precision for numerous animals of different species, young and adult, carnivorous and frugivorous. The animals, during the experiment, being subject neither to inconvenience nor fatigue, it might be assumed the heat they lost was equal to that which they reproduced. On analysing the products of respiration, it was found that they were changed as air is which has undergone combustion. The oxygen of the atmospheric air which was introduced into the cage was, in fact, combined with carbon, and formed carbonic acid. So far, therefore, as concerned this point, a real combustion may be considered as having taken place in the lungs. Thus much was inferred in general as to the source of animal heat from the discoveries of Lavoisier.

321. Chemical action accounts for total heat.—It remained, however, to verify this discovery by showing that the exact quantity of heat evolved in the animal system could be accounted for by the chemical phenomena manifested in respiration; and this Dulong accomplished.

After having determined the quantity of heat lost by the animal, he calculated the quantity of heat produced by respiration. The air which was furnished to the animal was measured by the gasometer, and the changes which it suffered were taken into account by analysing the products of combustion discharged through the water from the cage. These products were as follows :—

1. The vapour of water.
2. Carbonic acid.
3. Nitrogen.

The vapour of water analysed gave a certain quantity of oxygen and hydrogen, the carbonic acid a certain quantity of carbon and oxygen, and the nitrogen was sensibly equal to the quantity of that gas contained in the atmospheric air supplied to the animal. It followed that the oxygen of the atmospheric air which had been supplied combined in the lungs partly with carbon and partly with hydrogen, producing by respiration carbonic acid and the vapour of the water, being exactly the products resulting from the combustion of a lamp or candle. Now the quantity of heat produced by the combustion of given quantities of carbon and hydrogen being taken and compared with the quantity of animal heat developed, as given by the heat imparted to the water, was found exactly to correspond ; and thus it followed that the source of animal heat is the same as the source of heat in the common process of combustion.

When these researches were first made, it appeared that the quantity of heat actually developed in the animal system exceeded the quantity computed to result from the chemical change which the air suffered in respiration, and it was consequently inferred that the balance was due to a certain nervous energy or original source of heat existing in the animal organisation independently of the common laws of physics. Dulong, however, had the sagacity to perceive that the phenomenon admitted of a more satisfactory and simple explanation, and succeeded at length in showing that the difference which had appeared between the quantity of heat developed in respiration, and the quantity due to the chemical changes which the air suffered in this process, was accounted for by the fact that the quantity of heat developed in the combustion of hydrogen and oxygen had been under-estimated, and that when the correct constant was applied the quantity of heat due to chemical changes suffered by the air in respiration was exactly equal to the quantity of heat developed in the animal system.

442 PRACTICAL APPLICATIONS OF EFFECTS OF HEAT.

Since the establishment of the exact relations between heat and work, the results of Dulong's researches have been rendered still more striking by the investigations of Professor *Frankland*, of which a condensed review is given in the following table. It shows the amount of heat generated from so small a quantity as ten grains of certain foods during their complete combustion within the body, and the mechanical work equivalent to the heat thus produced.

Food.	Raises in combustion the temperature of 1 lb. of water through	Which is equal to lifting 1 lb. through
10 grains of dry flesh . .	13°12 F.	10·128 feet
„ „ albumen . .	12·85	9·920 „
„ „ lump sugar . .	8·61	6·647 „
„ „ arrowroot . .	10·06	7·766 „
„ „ butter . .	18·68	14·421 „
„ „ beef fat . .	20·91	16·141 „

Thus we prove that an ounce of fresh lean meat, if entirely burnt in the body, would produce heat sufficient to raise the temperature of about 70 lbs. of water 1° F., or a gallon of water about 7° F. But it must be added that, as the combustion which is effected within the body is not always complete, the actual effect is less than here indicated.

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